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FLYING QUALITIES DESIGN REQUIREMENTS FOR SIDESTICK CONTROLLERS

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Final Report for period October 1978 — August 1979

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Five flight test experiments using the variable stability NT-33A were sponsored by AFWAL/FIGC from May 1977 to June 1979, conducted by students of the Air Force Test Pilot School. This data has been correlated with previously published flying qualities information to form guidance on design of sidestick controllers. Preferred force and deflection gradients are indicated. There is an apparent influence of short-period frequency and roll mode time constant on the preferred sidestick characteristics. The results presented and discussed are for fighter configurations and tasks. The very limited amount of data on transport airplanes

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is discussed. The implications to the flying qualities specification are discussed, but it is concluded that there is insufficient data to formulate requirements. Data from the AFTPS experiments is presented in appendices to this report.

FOREWORD

This report was prepared by Mr. Black and Mr. Moorhouse of the Flying Qualities Group, Control Dynamics Branch, Flight Control Division. The effort was conducted under Program Element 62201F, Project 2403, Task 05, Work Unit 36. This is the final report for the time period October 1978 through August 1979.

The conclusions presented herein are based partly on previously unpublished work conducted by students of the Air Force Test Pilot School. Five flight test experiments using the variable stability NT-33A were sponsored by AFFDL/FGC from May 1977 to June 1979. Technical results of these tests, extracted from the project reports, are presented in Appendices B-E. The data collected is the result of contributions by a large number of people: the students of the AF Test Pilot School who conducted the experiments, listed by name in the data appendices; Major John Hoffman, Major George Muellner and Major Jim Tilley, AFTPS faculty advisors to the projects; and Stephen Smith and Lt David Maunder, AFFTC program managers. Each of the project reports additionally cited the considerable assistance received from the Calspan Corporation safety pilots and support personnel.

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LIST OF SYMBOLS

F_{as}	Lateral stick force, lb
F_{es}	Pitch stick force, lb
g	Acceleration due to gravity, 32.2 ft/sec
n_z	Normal acceleration, g's
p	Roll rate, deg/sec
q	Pitch rate, deg/sec
r	Yaw rate, deg/sec
α	Angle of attack, deg
β	Angle of sideslip, deg
δ_{as}	Lateral stick deflection, deg
δ_{es}	Longitudinal stick deflection, deg
δ_r	Rudder deflection, deg
δ_{rp}	Rudder pedal deflection, deg
ζ_{Dr}	Dutch roll damping ratio
ζ_P	Phugoid damping ratio
ζ_{SP}	Short-period damping ratio
θ	Pitch attitude
τ_R	Roll mode time constant
τ_s	Spiral mode time constant
ϕ	Bank angle
ω_c	Corner frequency of prefilter, rad/sec
ω_{DR}	Dutch roll natural frequency, rad/sec
ω_P	Phugoid natural frequency, rad/sec
ω_{SP}	Short-period natural frequency, rad/sec

SECTION I

INTRODUCTION

With the advent of fly-by-wire systems, interest in the use of sidestick or sidearm controllers has intensified. The controllers investigated, consisting of the handgrip from a conventional center (floor-mounted) stick controller usually mounted on a side console, are designed to be flown with motions of the wrist rather than the entire arm. The primary advantages are reduced pilot fatigue during and resulting from extensive maneuvering and increased instrument panel space/decreased cockpit size. These benefits have thus far stimulated the use of sidestick controllers primarily for more maneuverable aircraft; however, present trends indicate that their use may become more widespread in future years.

Limited research has been conducted as an add-on to other programs using sidestick-controlled aircraft. Unfortunately, little work has been done either in assembling a generic data base or in defining and matching optimal aircraft dynamics and sidestick controller dynamics from a flying qualities standpoint. In terms of experiments utilizing a generic variation of parameters, the AFFDL has sponsored work by both Calspan Corporation (Reference 1) and the Air Force Test Pilot School (AFTPS) (Reference 2-6) using the variable stability NT-33A. This work has been done with the intent of generating a data base to support development of criteria for MIL-F-8785B, Military Specification - Flying Qualities of Piloted Airplanes.

The first object of this report is to assemble and summarize the available data to support aircraft design, in the form of both design guidance and discussion of more general flying qualities criteria for inclusion in the specification. Section IV presents a correlation and analysis of available data. Much of the correlation is of a part of the total problem, assuming that other parts are satisfactory. There is an apparent correlation with a normalized force-deflection gradient, representing fraction of the total deflection per pound of force. This parameter assumes that the total deflection is satisfactory. The Section also

indicates some apparent trends that require additional data for verification. Section V presents guidance towards achieving a satisfactory design of a sidestick controller for fighter aircraft, with an example design problem presented in Appendix A. Section VI is a discussion of possible criteria for inclusion in the flying qualities specification. The discussion is mainly speculation on the apparent trends and tentative correlations presented in the earlier Section. The results are also contrasted with the very limited amount of data for transport configurations.

The reports of the AFTPS work have not been distributed, although a preliminary summary was presented at the 1978 AFFDL Flying Qualities Symposium (Reference 7). A second object of the present report, therefore, is to document those results. Appendices B-F contain the basic data from each of the tests together with the technical discussion. Each of the appendices is extracted from the appropriate AFTPS Letter Report with minimal editing.

SECTION II

HISTORY

Aircraft sidesticks are really nothing new. The original Wright Flyer could be considered to have a single-axis sidestick controller for control of pitch; many of the Wright's earlier designs used this type of controller. The first Wright aircraft sold to the US Army, however, had the wheel and rudder controller arrangement first used by Glenn Curtiss. This controller arrangement remains the prevalent arrangement today, particularily on aircraft not designed for extensive maneuvering. The other common arrangement, center stick and rudder, dates from Armond Deperdussin's racing monoplanes of 1912 (according to Garber of the Smithsonian). This control arrangement quickly became the standard for more maneuverable aircraft, and remains so today.

During the post WWII period, sidearm controllers were tried experimentally as "formation sticks", on aircraft such as the XB-48. In this capacity, they were used for gentle maneuvering by providing inputs to the aircraft through the autopilot rather than through the conventional flight control system. The conventional controls were used for takeoff, landing and maneuvering the aircraft, and also when the autopilot was not in use.

In 1957 the National Advisory Committee for Aeronautics (NACA) modified a T-33 aircraft so that the front seat pilot could fly the aircraft with a sidestick controller (Ref 8). This controller was independent of the center stick but was usable as a primary flight controller. In this design, roll control was from the conventional left-right rotation of the stick, but pitch control was via an up and down motion of the stick, pivoting about the wrist. This same arrangement was later incorporated in the USAF variable-stability NT-33A for sidestick research conducted during the early 1970's.

The NACA study found that the offset controller location was comfortable to the pilot and that the aircraft was flyable with this arrangement. The lateral arrangement was considered comfortable, but the use of vertical displacement for pitching was "strange and uncomfortable especially when large stick motions and high force levels are required".

The first operational aircraft to again use a sidestick controller to directly fly the aircraft was the X-15. In the X-15 arrangement, the sidestick was coupled to the center stick "at the non-linear pitch mechanism arm through the separate pitch and roll hydraulic boost actuators in order to reduce aero (side) stick pilot control forces and synchronize both stick displacements" (Ref 9). The intent of the sidestick was to allow the X-15 aircraft to be more easily maneuvered during longitudinally accelerated flight such as boost and re-entry. The design of the sidestick was such, however, that it could be used at any time during atmospheric flight at the pilots discretion.

Much of the development work on the X-15 sidestick was done on a JF-101A aircraft in 1960 and 1961 (Ref 10). Once again a pitch pivot at the wrist was used on the stick, with the roll pivot at the stick base. For this effort, a human factors study of wrist agility was also made to define good pivot locations. The study was very extensive, and led to several conclusions, including optimized pitch and roll gearings and force-deflection gradients. These results will be discussed further in the next section.

During 1966-68, the Air Force Flight Dynamics Laboratory sponsored a pitch-axis fly-by-wire test program on a JB-47E. During the second phase of this program a sidestick controller was mounted on the pilot's (or copilot's) left side ejection seat arm. Evaluation pilots commented favorably on the system, particularly the "ease and preciseness of control" (Ref 11).

During this same time period, two F-106B aircraft were modified into variable-stability trainers. These aircraft were flown with sidestick controllers as well as the normal stick. Nothing further is known about this project.

In 1969 the Martin Marietta Corporations's Baltimore Division under contract to the Air Force Aerospace Research Pilot School (now Air Force Test Pilot School) designed, built and installed a sidestick fly-by-wire control system in two F-104D's. These aircraft were evaluated in flight by ARPS. The results were reported at the 1970 annual symposium of the

Society of Experimental Test Pilots (Ref 12) and will be referred to in the next section.

The USAF variable stability NT-33A aircraft has been used extensively for flying qualities research. In 1974 it was equipped with a variable-force, variable-motion sidestick controller as documented in Reference 13. Experiments on this airplane form the main data base for this report. At this writing the aircraft is configured with a base-pivot (pitch and roll) stick which may be either fixed or displacable.

The first production aircraft to use a sidestick controller is the F-16. Both fixed and limited-motion sidesticks have been evaluated both in the YF-16 prototype and the F-16A full-scale development aircraft (Ref 14).

Although the emphasis is toward fighter applications, sidesticks have been used as primary controllers on other classes of aircraft, too. A sidestick design was used in the C-141 Fly-By-Wire Program (References 15 and 16). Reference 16 states that the human factors development of the sidestick controller relied on results from References 10, 17 and 18. Very few details are given of the sidestick characteristics finally chosen; however, the aircraft with fly-by-wire control system was evaluated in a variety of tasks. There was, apparently, little adverse comment about the sidestick. In a similar application, a sidestick was included in an experimental digital fly-by-wire control system evaluated by Aerospatiale in the No. 1 Concorde (Reference 19). A problem with the installation was that the left-hand sidestick and the right-hand throttles were farther apart than desired. The total system, however, was evaluated as having excellent handling qualities, in ten hours of flight test over a wide range of conditions. Along with the earlier cited use as formation stick, these examples represent application to large aircraft which are not highly maneuverable.

On the other end of the spectrum, sidestick controllers are used in two light aircraft (the Rutan VariEze and the Bede BD-5 series of aircraft) and one experimental light twin (the Rutan model 40 Defiant which, incidentally, uses a left-hand operated sidestick for the pilot and a right-hand operated sidestick for the copilot). Qualitative evaluations have been conducted on the BD-5 aircraft (both piston-engined and jet-powered, Refs 20 and 21) and the results are also discussed in the next section.

SECTION III

DATA AVAILABILITY

The preceding section gives an indication of the number of programs that have investigated sidestick controllers. In this section, we will comment on the usefulness of the data to support development of flying qualities criteria.

A. Published Data

The majority of programs discussed in Section II, plus the references available, have considered sidestick controllers for a specific application. As such, the result is frequently a qualitative assessment or a single data point. The physiological factors of neutral displacement, displacement limits and force levels are available from these programs. The Calspan study reported in Reference 1 is the only generally available report on the interaction of airplane dynamics with sidestick controller characteristics. In this study a general matrix of four response-force values versus three force-deflection values was investigated for a simulated Level 1 aircraft configuration. The effects of reduced short period damping and increased roll mode time constant were evaluated for selected controller characteristics. This report was a start on acquiring a generic data base for flying qualities applications.

B. Unpublished Data

Following the work reported in Reference 1, the Flight Dynamics Laboratory began sponsoring a series of experiments (References 2-6), also using the variable stability NT-33A. These experiments were flown at the AF Test Pilot School as student projects. The projects were defined by the students with guidance from AFFDL's Flying Qualities Group and Calspan's project engineer. The student teams included both pilots and flight test engineers, with the pilots doing the flying qualities evaluations. Calspan provided guidance in all phases of the experiments, engineering safety pilots, and also supported the aircraft operations.

The results of the flight test experiments were documented in Letter Reports to the Flight Dynamics Laboratory. The first of these Letter Reports was also issued as a Flight Test Center Technical Report, and a summary of the first three was presented at the Flying Qualities Symposium

in September 1978 (Reference 7). It was decided, however, that the individual Letter Reports would not be distributed because of the variety of constraints under which they were produced. Although inexperience, learning curves, time limitations, etc., tend to increase slightly the number of questionable data points as compared to a "professional" study, the data is believed to be generally valid when viewed as a whole. This data is therefore published in Appendices to this report. The range of parameters tested is indicated in Table I, and a short summary of each of the AFTPS experiments follows:

Test by Class 76B (Reference 2, results presented in Appendix B)

A matrix of both longitudinal and lateral force and deflection characteristics was evaluated in tasks representative of Flight Phase Categories A (precision and gross maneuvering) and C (approach and landing). The values tested generally filled in the matrix tested in Reference 1 with the same aircraft dynamics. There were, however, minor differences in the gradients, the non-linearities and the breakout forces.

Test by Class 77A (Reference 3, results presented in Appendix C)

This experiment continued the previous tests but expanded the matrix to include more deflection and heavier forces. Included in the results is an excellent discussion of the factors affecting the ratings for various side-stick controller characteristics.

Test by Class 77B (Reference 4, results presented in Appendix D)

This test investigated the effects of varying the corner frequency of first-order lag prefilters in both the longitudinal and lateral axes (identical prefilters were used in each axis). The optimum response/force gradients from the previous tests were used, with two values of deflection/force gradient.

Test by Class 78A (Reference 5, results presented in Appendix E)

This test investigated a matrix of three short period frequencies with a medium roll mode time constant and three roll mode time constants at a medium short-period frequency. Controller characteristics were two response/force gradients in each axis with a constant force/deflection gradient value.

TABLE I. Summary of Parameter Variations Tested in AFTPS Experiments

CONFIGURATION	AFFDL-TR-75-39		SPRING 77		FALL 77		SPRING 78	FALL 78	SPRING 79	FALL 79
DESCRIPTION	PHASE A	PHASE C	PHASE A	PHASE C	PHASE A	PHASE C				
n_z/α	33	7	33	7	20	3.7	--***	29	22	29
ω_{sp} ζ_{sp}	5,3.7 .6,.25	2.2 .5	5 .6	2.2 .5	6 .6	3.3 .2	-- --	3,5.5,10 .65	2.7,6.1 .7	1.8,2.6,5.6 .7
ω_p ζ_p	.09 .05	.15 .05	.09 .05	.15 .05	-- --	-- --	-- --	-- --	.08 .1	.09 .05
τ_r	.1,.2	.5	.2	.5	.35	.5	--	.2,.35 .95	.3	.35
τ_s	∞	∞	∞	∞	∞	∞	--	∞	∞	∞
ω_d ζ_d	3.2 .4	1.2 .25	3.2 .4	1.2 .25	2.3 .16	1.7 .07	-- --	4 .35	3.2 .47	3.2 .35
ϕ/β	.5	3	.5	3	.4	3	--	2	2.8	2
δ_{es}/F_{es} (deg/lb)	0,.5, .91	Same	.2,.5, .7,.91	Same	.18,.38 .57,.73 .96	Same	.2,.7	.84	.93	.3,.58,.9
δ_{as}/F_{as} (deg/lb)	0,.77 1.43	Same	.3,.77 1.08, 1.43	Same	.12,.42 .77,1.09 1.35	Same	.3,1.05	1.05	.416,1.05 2.5	.56
$^*F_{es}/n_z$ (lb/g)	4,6,9 13	10,13 18,26	3,3.5 5,8	10,12	3.5,4.75 7,10,17	17,26, 38.5, 52.5, 83	6	5,10	5,10.75	5,8
$^*F_{as}/p$ (lb/deg/sec)	.075, .095, .117, .15	.1,.12 .16,.2	.06, .075, .093, .15	.1,.14	.056, .091, .14,.23 .37	.097, .13, .22, .32, .62	.143	.1,.2	.13**,.32	.2

Comments

* Corresponding gains, dual gradient with break at 4 lbs (long), 3 lbs (lat), initial slope shown

** Gradient reduced to 1/2, 1/3 and 1/4 at 3 lbs

*** Prefilter corner frequencies of 2, 4, 8, 12, 16 rad/sec in both pitch and roll axes

Test by Class 78B (Reference 6, results presented in Appendix F)

This test investigated a matrix of lateral force/deflection gradients and force/response gradients against the two preferred pairs of longitudinal short period frequency and sidestick force/deflection from the previous experiment. Additionally, in the second phase, two non-linear longitudinal force/deflection gradient ratios were evaluated.

SECTION IV

DATA CORRELATION AND ANALYSIS

In this section, data from several specific test programs shall be shown and compared. Additionally, recommendations and conclusions from these programs will be discussed where applicable. The test or research programs to be addressed herein are primarily for the following aircraft:

JF-101A

BD-5 series

F-104D SSCS (Sidestick Control System)

F-16A (Movable Sidestick Evaluation)

NT-33A Sidestick Research Programs

A. Evaluation Tasks Used.

Prior to actually presenting and addressing the data, the tasks used in the evaluations must be discussed as the use of the data may be limited by these tasks.

An extensive series of tasks were performed during the F-104D SSCS and the BD-5J evaluations. These tasks included aerobatics, formation flight and landings for both aircraft. Additionally, the F-104D SSCS was evaluated in X-15 profile flights (a 270° overhead approach with high key at 23,000 feet), "dirty L/D" approaches (a high-drag straight in approach from 11,700') and zoom profiles. These are all presented pictorially in Figure 1. The BD-5J was evaluated in basic fighter maneuvers (BFM), air-combat maneuvering (ACM) and air-combat tactics (ACT), to assess its potential as a low-cost trainer. The F-104D SSCS and both the BD-5 and BD-5J evaluations generated a significant amount of qualitative data.

The F-16A has been evaluated with a movable sidestick in operational-type flying, and in a type of tracking known as "handling qualities during tracking", or HQDT (Reference 22). HQDT consists of tightly tracking a target aircraft which is flying a "canned" maneuver such as a constant 2g turn, a loaded reversal, or something similar. The purpose is to gather closed-loop tracking data in an environment similar to the operational environment. It should be emphasized that the type of tracking done in HQDT testing is not operational air-combat-type tracking. Thus while good

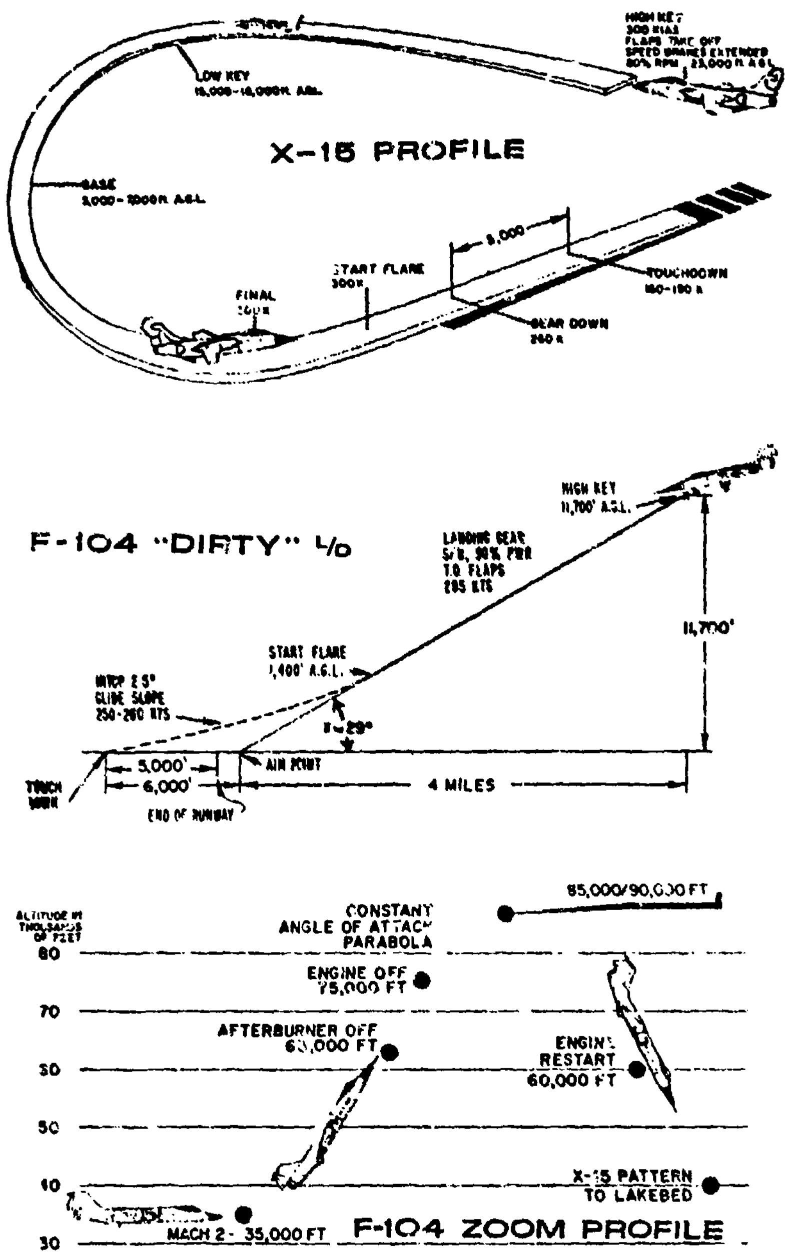


Figure 1: Some F-104D SSCS Evaluation Tasks (Illustrations from Ref. 12)

HQDT tracking may imply good tracking handling qualities it does not guarantee combat effectiveness. From a specification standpoint, however, HQDT evaluations are much more closely related to operational use than simply specifying open-loop parameters such as short-period frequency and damping. Nevertheless, HQDT must be viewed simply as a method of generating both qualitative and quantitative data on pilot preferences, workload and task performance, not as an evaluation of operational excellence or suitability.

For the JF-101A used in the X-15 sidestick development program, an IFR 2-axis tracking task (similar to localizer and glideslope tracking on a flight director) was used for evaluation. This data was gathered both on the ground (using the JF-101A as a fixed-base simulator) and in flight. Additionally, some landings were performed in the JF-101A using the sidestick, though no quantitative data were gathered during approach and landing.

The NT-33A has evaluated sidestick characteristics primarily in HQDT tracking with some additional data gathered for basic aerobatics, approach and landing tasks. This data is the most complete, comprehensive set available; is presented in "raw" form in Appendices B-F. It should be noted that the majority of this data has been generated during five student research projects at AFTPS, thus some variability in the results is to be expected.

D. <u>Sidestick Deflection Geometry, Location and Control Switches</u>.

The majority of the information available here comes from the F-104D SSCS and the NT-33A. According to Reference 12, given a choice the pilot usually will select "about 12° left, or inboard, of vertical (as a roll neutral point). This is because of the limited freedom of the human forearm to rotate in the outboard direction". Aircraft control was deteriorated if the pilot's hand moved "beyond 5° to 8° right of vertical". Additionally, , the pilots usually selected 17° forward pitch as neutral, or about 10° more than the natural neutral position of the human wrist. Pilots selected this in order to insure aft rotation capability, as this capability is very limited from the wrists natural neutral position.

In the F-104D SSCS the available forward motion was half (1" vs 2") of the available motion to the rear. Surprisingly, pilots made no objection, even viewing it as natural and acceptable. Experience with the F-16A movable sidestick supports this finding, even accentuating the difference far more. A result of the latter program (Ref 14) is that forward stick motion slightly less than 1/9th of the aft stick motion (.019" vs .178") is acceptable. It is felt that since very little flying is done with forward stick pressure, and since wrist geometry using a 17° forward neutral position favors aft motion, using limited forward motion presents no problems.

Many early experiments, including the first NACA T-33 studies and early NT-33A experiments used a sidestick having a pitch pivot at the wrist (i.e., up-and-down motion along an arc centered at the wrist). This is compared to a base-pivot stick in Figure 2. While this would seem to be the natural location for the pitch pivot, pilots actually prefer a conventional base-pivoted stick, claiming that an up-and-down motion of the wrist is unnatural (Ref 9).

Studies with the F-16A, F-104D SSCS, BD-5 and the NT-33A all seem to indicate that for various reasons the pilot's forearm should be supported, and that the position of this support is important. To quote Reference 12:

> "The top of the stick should be no more than one inch above the forefinger. The vertical position of the hand is dictated by the necessity to firmly rest the forearm on the armrest. Thus, the height of the switch above the pilot's hand is determined by the size of the pilot's hand or the bulkiness of his clothing. In order to have easy and positive access to the switch or button, the device must be one inch or less above the forefinger. An operational sidestick should have a variable control stick length or variable armrest height to allow precise control of the position of the top of the control stick and the top of the pilot's hand."

Control switches or buttons located on the control stick should have breakout forces "significantly, at least 50%, below the breakout forces of the controller itself", again according to Reference 12. This is to prevent

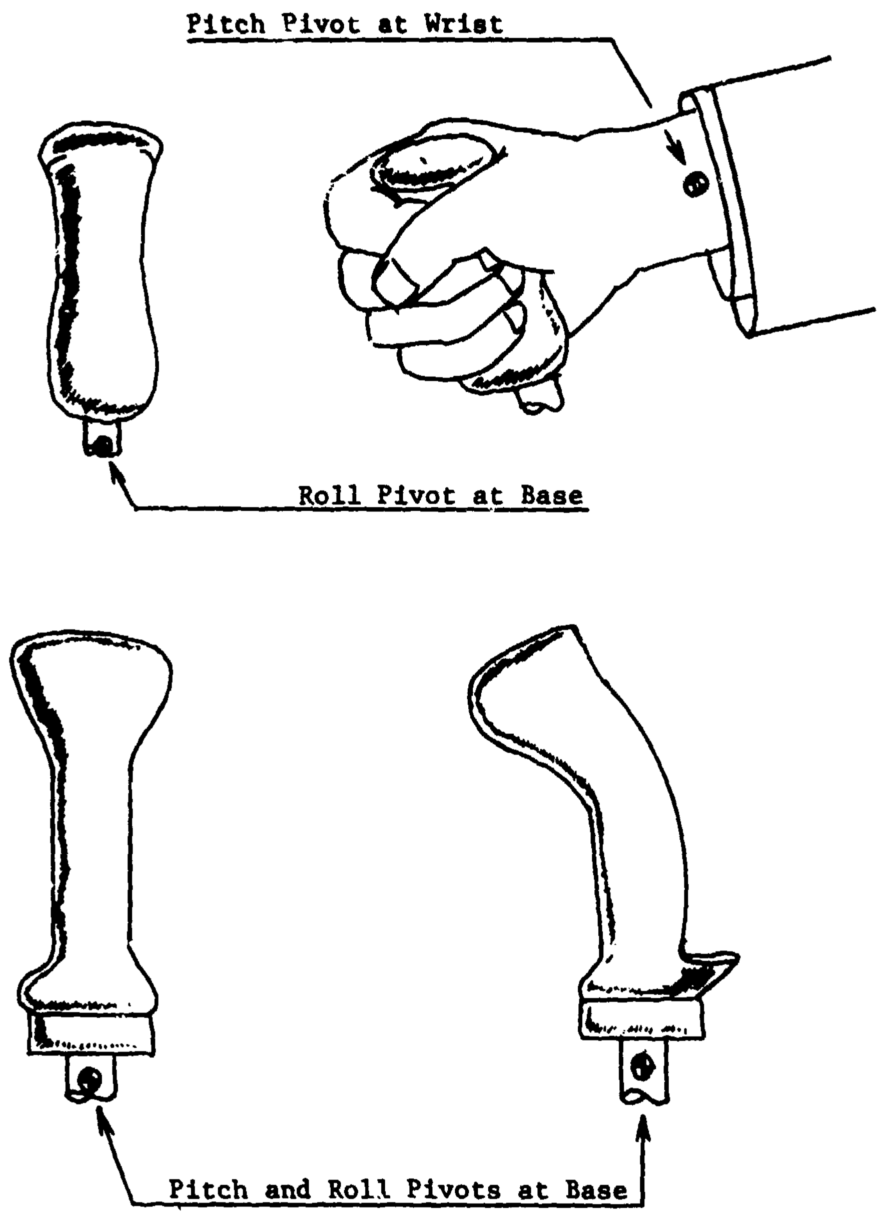


Figure 2: A Comparison of two Pitch and Roll Pivot Location Sets

unintentional control inputs during switch operation. Additionally, the F-104D SSCS program found that force-command switches are unacceptable; switches should have motion associated with their activation in order to provide an instantaneous, positive indication of activation.

Some studies have indicated that identical dual control sticks, one per side, should be used. The authors of Reference 12 suggested this. However, no complaints have arisen in other sidestick programs so this is not felt to be necessary.

C. Longitudinal Deflection-Force and Force/Response Characteristics.

It should be stated from the outset that despite the use of a "fixed" stick on the F-16 prototypes and full-scale development aircraft, all available sources which have tested both fixed and "motion" sticks in flight have found that pilots definitely prefer motion sticks. The question to be answered then becomes how much motion? The use of a fixed stick is preferred in a fixed-base simulator, though, and it is felt some designers have taken the attitude "if the pilots like it in the simulator they'll like it in flight". Reference 10 further elaborates on this:

> "The electric sidestick coupled with the MH-90X control system was evaluated by twelve pilots from NASA, USAF, Boeing Aircraft, McDonnell Aircraft and the USN. Five flew the electric stick exhaustively to assist in determining optimum design parameter values. These five evaluation pilots each had four to eight hours ground time in the JF-101A cockpit. This ground time served two purposes: (1) it provided valuable cockpit familiarization for pilots who, although current in the JF-101A airplane, did not routinely fly it. (Pilot familiarization with the special cockpit equipment saved valuable flight time by eliminating the false starts usually associated with new equipment installations.) and (2) the function of this ground time was to get pilot performance data during simulated problem runs on the ground. In order to make simulated problem tracking runs, a Reeves Electric Analog Computer was connected into the autopilot giving a two-axis simulation which could be controlled by either the center stick or the electric sidestick.

"Problem tracking scores were 10 to 100 times poorer on the ground than in the air. Since the most important difference between the ground and air environments is the acceleration and motion cues received by the pilot in actual flight, it was concluded that these cues are extremely important for precise tracking.

"Pilots showed a tendency to develop a special flying technique on the ground, a bang-bang, pulse-type control, particularly with the force stick, which was not at all typical of the control technique used in the air.

"In general, a very skeptical attitude was developed toward the ground simulator work as a result of these observations which was further reinforced by the pilot opinion of the force stick. Every pilot who first flew both the rigid force stick and the moving stick on the ground simulator preferred the rigid force stick over the moving stick, both for maneuvering and trimmed flight. However, after actually flying both stick types through the tracking problems, every pilot reversed his opinion preferring the moving stick for maneuvering flight. Some pilots enjoyed flying the rigid stick in low-demand flying, slow maneuvering, or trimmed flight; but all pilots rejected it for the more demanding tracking problems."

How much motion to use is a totally different matter. Experience with the YF-16 indicates that for a given force/response gradient some motion improves pilot opinion; however, additional motion degrades it. This tends to indicate that an optimum range of deflection/force gradients exists. The NT-33A sidestick experiments conducted by AFTPS for AFFDL have attempted to isolate this area, and indeed have found a region of longitudinal deflection/force gradients which appear to be good. The reader is referred to Appendices B-D for the uncorrelated data.

Reference 7 presented a summary of the data from the first three AFTPS experiments, as well as some observations concerning the data.

Figures 3 and 4, from that reference, represent the configurations tested and the corresponding longitudinal force/response gradients. Figure 5 shows the pilot ratings for the matrix of test conditions shown in Figure 3. Also shown are Smith's iso-opinion contours and evaluation of adequate and poor regions. In the present report, we prefer to express the correlation quantitatively in terms of the initial gradient of the force/response curve. We have assumed that the pilot is most sensitive to the initial slope for any task involving tracking. This parameter is not to be taken as being independent of other characteristics. Acceptance of the initial slope requires that any change in the gradient and also the breakpoint be compatible, as discussed later. Taking this approach and adding the data from Reference 1 (Figure 6) yields Figure 7. Notice that each individual pilot rating value is shown. The most obvious interpretation of these results is that there are no well-defined boundaries to be drawn.

The F-16A movable sidestick is not in any area of acceptable ratings in Figure 7. Calculations based on Reference 14 place the F-16A movable sidestick deflection/force gradient at 0.065 degrees per pound, far below recommended values. Still, Reference 14 indicates that pilots expressed a preference for the F-16A movable sidestick compared to the standard fixed stick. Although actual pilot opinion ratings were not given, we have treated it as Level 1 because of the improvement over the fixed stick that is in operational use. The answer may lie in using the technique suggested by Duprey (Ref. 23). In evaluating data from several sources, Duprey found it convenient to use normalized stick deflection/force gradients. For the longitudinal axis this normalized gradient consists of the actual longitudinal stick deflection/force gradient divided by the available stick deflection from the neutral position to the full aft position. The resulting parameter, in inverse pounds, is then equivalent to the fraction of stick deflection per pound of applied force. It will be referred to during the remainder of this report as the "normalized deflection/force gradient". The inverse of this parameter is just as meaningful - being the force if the initial deflection/force gradient were continued to the maximum deflection. This is not the same as the maximum force if there is a break in the gradient, and it would be necessary to distinguish the two. We have, therefore, used the normalized gradient.

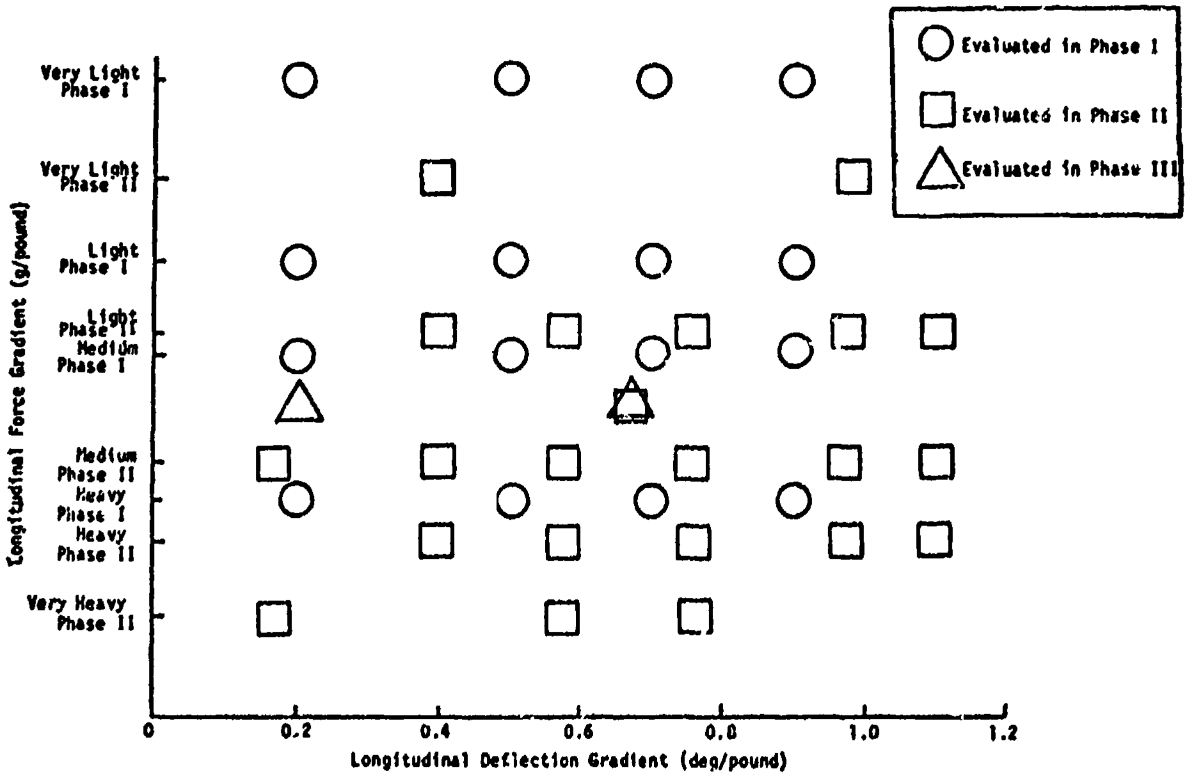


FIG 3: TEST MATRIX FROM REFERENCES 2, 3 AND 4

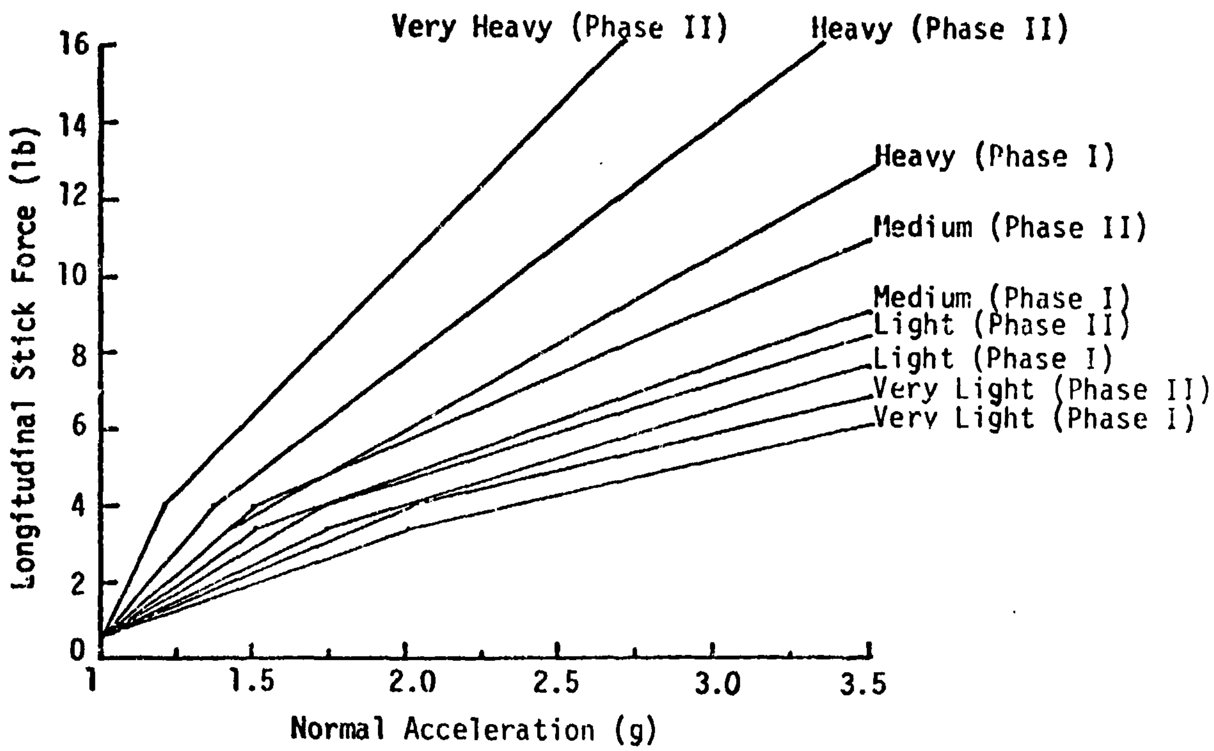


FIG 4: LONGITUDINAL FORCE-RESPONSE GRADIENTS FROM REFERENCES 2, 3 AND 4

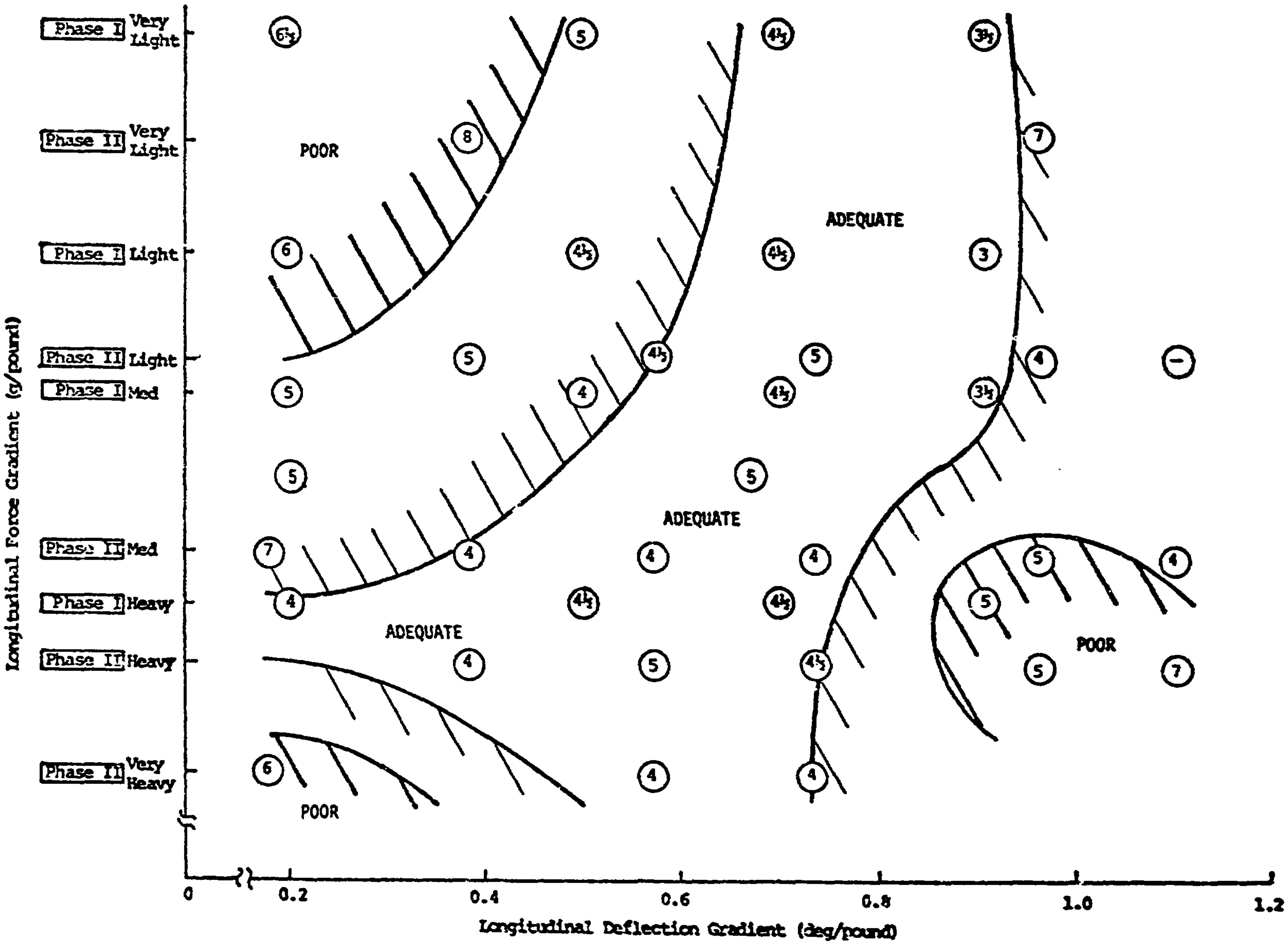


FIG 5: SUMMARY OF PILOT RATINGS FROM REFS 2, 3 AND 4, WITH SMITH's ISO-OPINION CONTOURS
(Figure Courtesy Ref 7)

Symbol	F_{ES}/δ_{ES}
F	Fixed
S	2.0 lb/deg (27 lb/in.)
L	1.1 lb/deg (15 lb/in.)

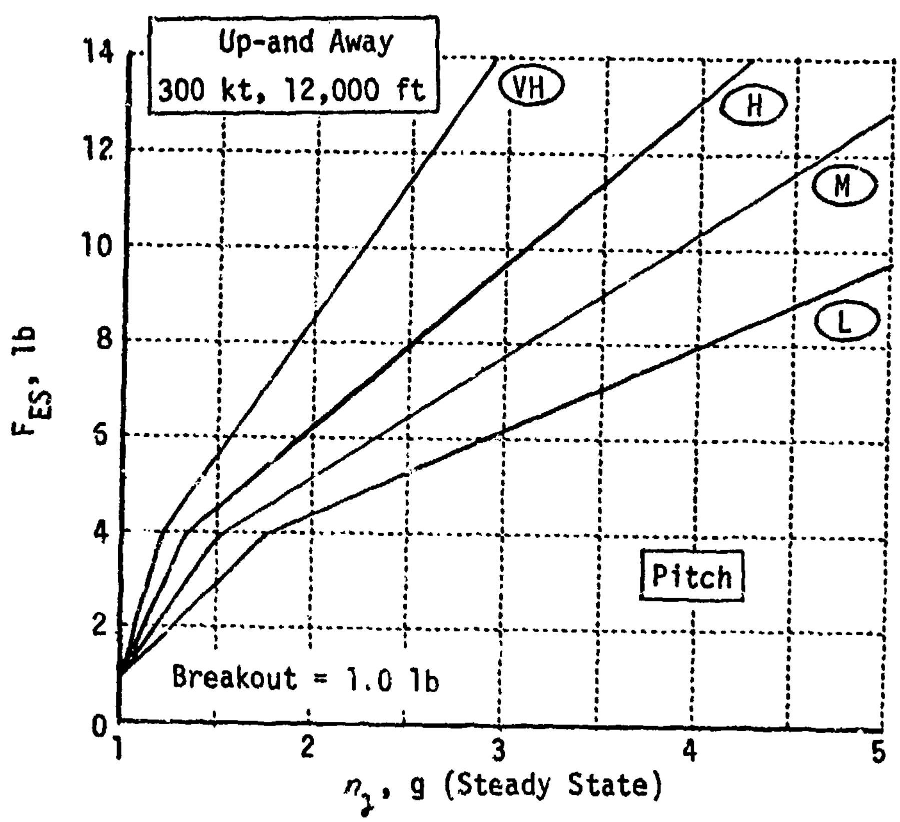


FIG 6: LONGITUDINAL FORCE-DEFLECTION AND FORCE-RESPONSE GRADIENTS FROM REFERENCE 1 (Figures from Reference 1)

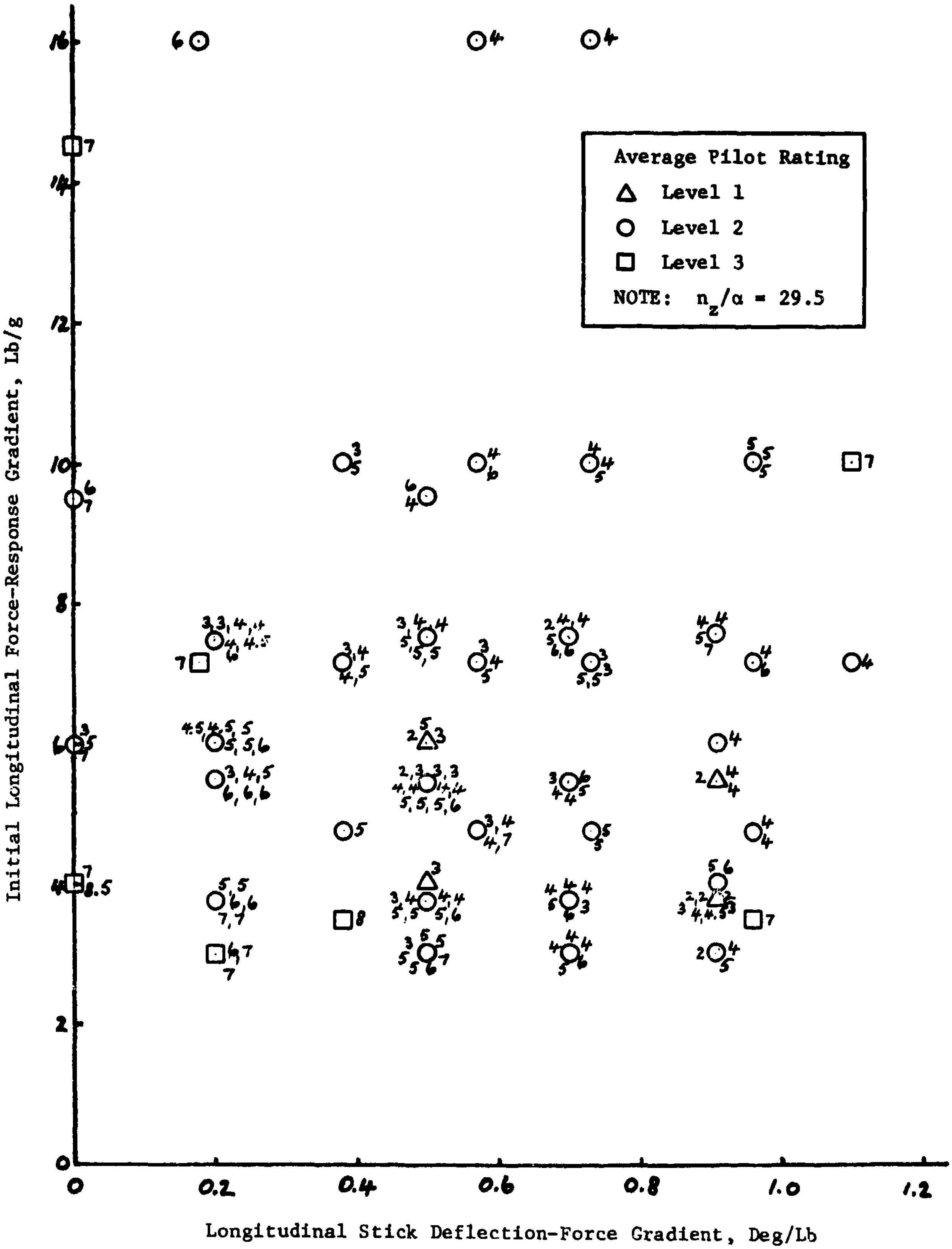


Figure 7: Summary of Results from References 1-4, Air-to-Air

Figure 8 represents a recasting of Figure 7 based on this method. The F-16A movable sidestick (a normalized deflection/force gradient of 0.0335 lb^{-1}) and JF-101A (0.0561b^{-1}) points are also shown on this figure. Results from the F-104D SSCS program qualitatively support this method; the heaviest stick force gradient when normalized resulted in a value of 0.081 lb^{-1}; Reference 12 indicates that the high forces (i.e., this force gradient) are acceptable for most tasks and adds, "As a general comment, we have underestimated the strength of the pilot". Therefore, a usable region of .03 lb^{-1} to .08 lb^{-1} seems plausible at this time, with the lower portion of the range being favored. We postulate, then, that the 'optimum' is actually a normalized region. This result would also require thatthe stick neutral position and total stick travel be within allowable ranges which need to be defined of course. Recommendations for neutral position and maximum stick travel are discussed in this report, which leaves the possible requirement to define mimimum allowable stick travel. We may speculate that it is likely to be a very sensitive function of airplane configuration and mission. In terms of general guidance, we suggest that the stick travel must be enough to be easily perceptible to the pilot and sufficient to form a definite stop at the travel limits.

During the NT-33A experiments, breakout forces of 1/2 lb were used and found acceptable. Conflicting data exists concerning the use of higher breakout forces; References 12 and 14 indicating no problems while Reference 2 disfavors them.

Two-segment pitch force/response gradients have been evaluated on the F-16A (movable sidestick) and the NT-33A. On the NT-33A, a halving of the stick force gradients for forces greater than about 3 lb (absolute) stick force was used. During the spring 1979 AFTPS project (Ref. 6) 1:1 and 4:1 longitudinal gradients were also evaluated and appear to be unacceptable.

D. Effects of Short-Period Dynamics

As an example of the interdependence of many parameters, Figure 8 might be used to suggest a range of 4 to 15 lb/g as being acceptable for the initial longitudinal force/response gradient if it were considered an independent parameter. In fact, the acceptable range has been found to be a function of airplane dynamics, i.e. short period frequency. During the fall 1978 AFTPS experiments (Ref. 5) three different short-period frequencies

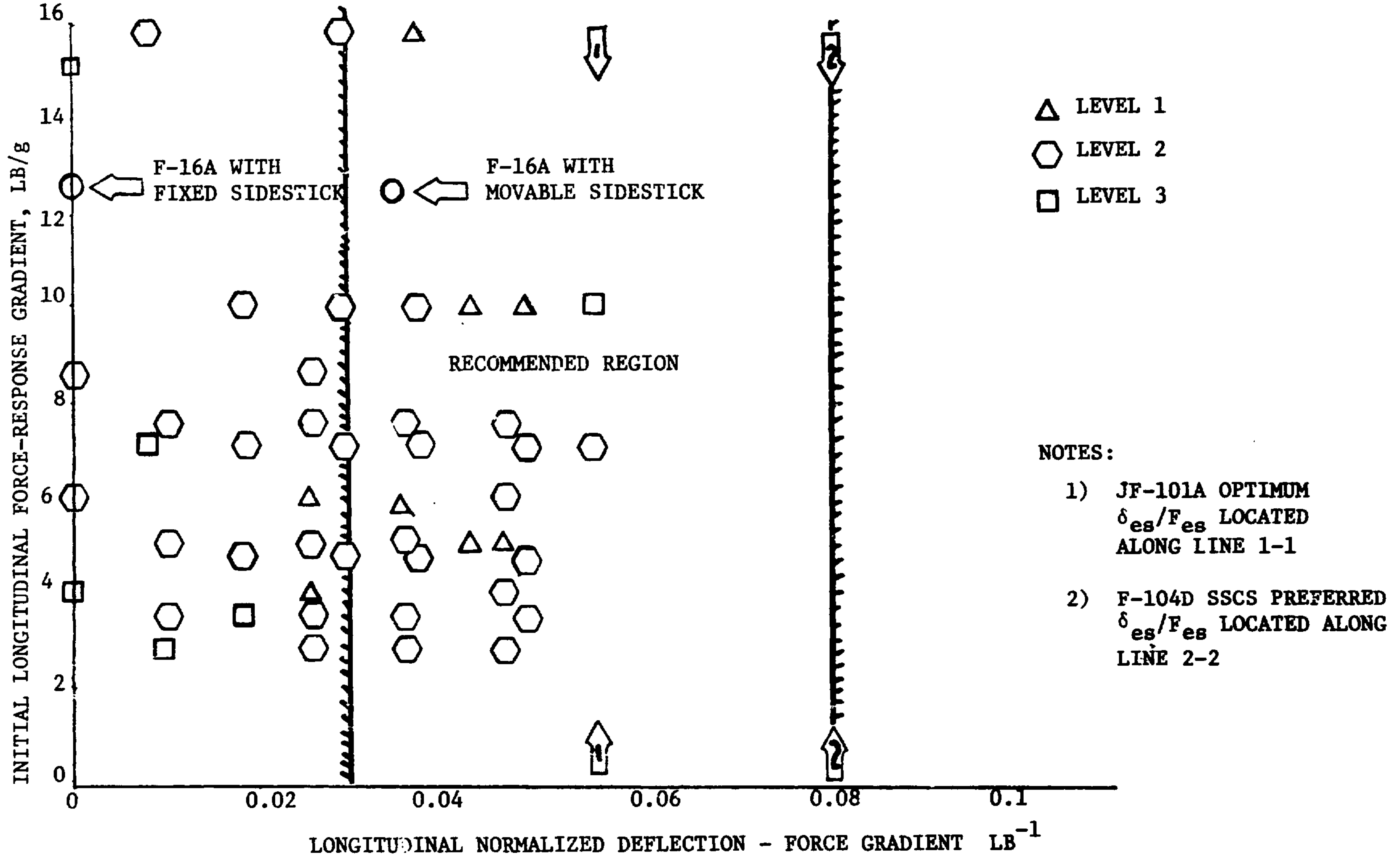


FIGURE 8: LONGITUDINAL RESPONSE vs NORMALIZED FORCE-DEFLECTION GRADIENTS

(2.6, 5.2 and 10 radians/second) were evaluated against two different longitudinal force/deflection gradients (5 and 10 lb/g, with the gradients halved at 3 lb absolute) for Category A tasks. For the NT-33A's nominal value of n_z/α (29.5g/rad), according to the current MIL-F-8785B (Reference 21) 2.6 radians/second is Level 2, and 5.2 and 10 radians/second are Level 1. With the sidestick controller, however, the 10 radians/second short-period was rated as Level 2 with the comment that it was too fast. The 2.6 and 5.2 radian/second short-peridd frequencies were rated Level 1, but only when paired with 5 and 10 lb/g stick force gradients, respectively. During the spring 1979 experiment, the 2.6 radians/second and 5 lb/g configuration was further identified as the preferred longitudinal configuration, based on preliminary data. It may be conjectured that the preference for lower frequencies reflects the absence of forearm and stick inertia effects which would be present in a center-stick-controlled aircraft. In commanding a rapid pitch input to such an aircraft, the pilot must overcome the inertia of his arm and the stick, thus he wants a "fast airplane" to make up for the filtering effect of his arm and the stick. In fine tracking with a center stick the pilot will rest his arm, typically on his knee, to reduce this problem. The inertia of the center stick is still greater than for a sidestick, so that we may still expect an effect even in fine tracking. When using the sidestick, however, these effects are not present so that a higher-frequency airplane seems to have a more abrupt response to control inputs. The pilot now prefers the airplane itself to act as a filter, smoothing the responses to his inputs. Thus, the pilots may prefer a lower-frequency aircraft when using a sidestick, compared to the preferred frequencies using a center stick on which MIL-F-8785B is based.

Based on private conversation with the authors, Chalk feels that this effect can similarly be addressed by a criterion on peak pitch acceleration response to stick force, $\left| \frac{\ddot{\theta}}{F_s} \right|_{max}$. Reference 25 elaborates on this and the idea also is discussed in Section VI of this report. Additionally, the work of Smith and Geddes (Reference 26) may be applicable, if one considers a lower airplane short-period frequency as a filtering effect on pilot inputs.

The data from the fall 1978 AFTPS experiment and a suggested range of short-period frequencies versus longitudinal stick force/response gradients is shown in Figure 9. References 20 and 21 suggest the lower F_s/n_z boundary, while Reference 5 suggests the lateral and upper boundaries. Preliminary data for the 2.6 and 5.2 radians/second short-period configurations generated during the spring 1979 AFTPS experiment (Ref 6) suggest that the recommended region may be smaller than first thought. This is shown by the dotted lines in Figure 9.

E. Roll Deflection/Force Gradients, Response, and Control Harmony.

During the first four AFTPS student projects on the NT-33A, pilots consistently complained about directional wandering and "pendulum" effects (i.e., the tendency of the pipper to oscillate like a pendulum because the pilot's line of sight through the pipper is below the roll axis of the aircraft). There is thus an additional question mark which needs to be placed against the lateral-directional results.

During the spring 1979 AFTPS experiment several lateral deflection/force and force/response gradients were tried with two previously liked sets of longitudinal dynamics and gradients (Ref 6). These data are shown in Appendix F. Based on these and previous data several observations can be made. Figure 10, taken from Reference 7, summarizes the lateral force/response gradients used on the NT-33A during the first three experiments and figure 11 shows the same data from Reference 1. Figure 12 shows pilot ratings for all the lateral force/deflection gradients from References 1-6. Rather than attempting to form iso-opinion contours for the results shown, it was decided to try a normalizing technique analogous to that used longitudinally. If this procedure is employed, an acceptable range of lateral normalized deflection/force characteristics is indeed found to exist. In Reference 4 an "optimum" configuration ("configuration X") is recommended; its normalized gradient is found to be .0325 lb^{-1}. It should be noted that this number is obtained by using the total center-to-left-stop deflection of 20^{o}, a soft stop is used at 12^{o} when moving the stick to the right though the deflection/force and force/response gradients are symmetric. Data from the first AFTPS experiment (Ref 2) indicate preferences for values of .054 lb^{-1} with a longitudinal normalized deflection/force gradient of .035 lb^{-1}, and values of .0715 lb^{-1}

RECOMMENDED REGION INSIDE BOUNDARIES

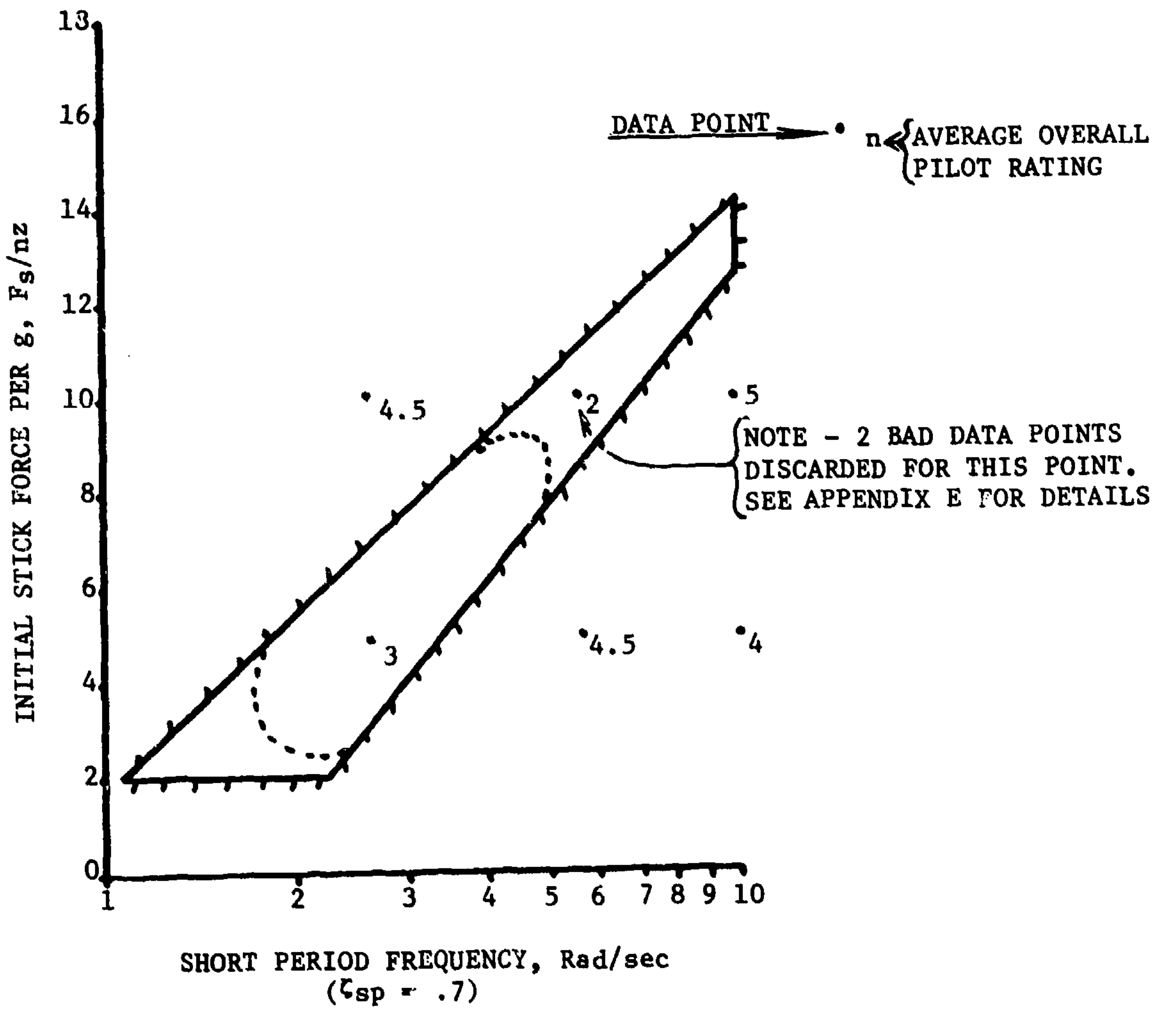
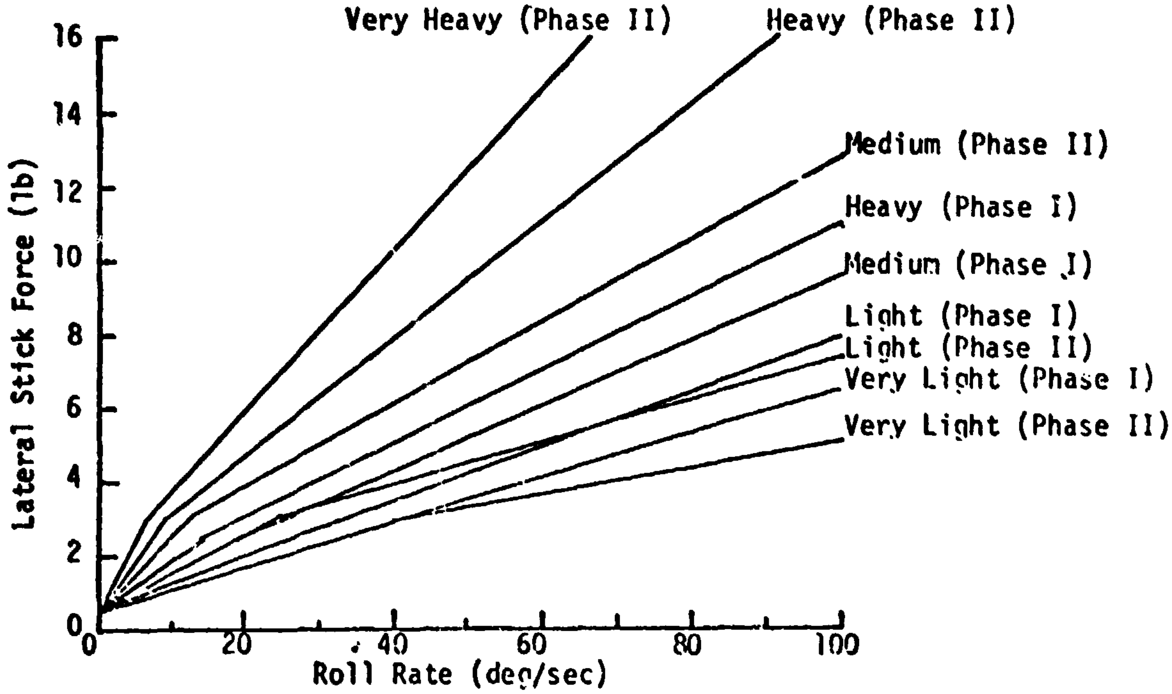


FIGURE 9. Short-Period Frequency vs Longitudinal Force/Response Gradient

FIG 10: LATERAL CONFIGURATIONS EVALUATED
IN REFS 2 AND 3 (FIG FROM REF 7)



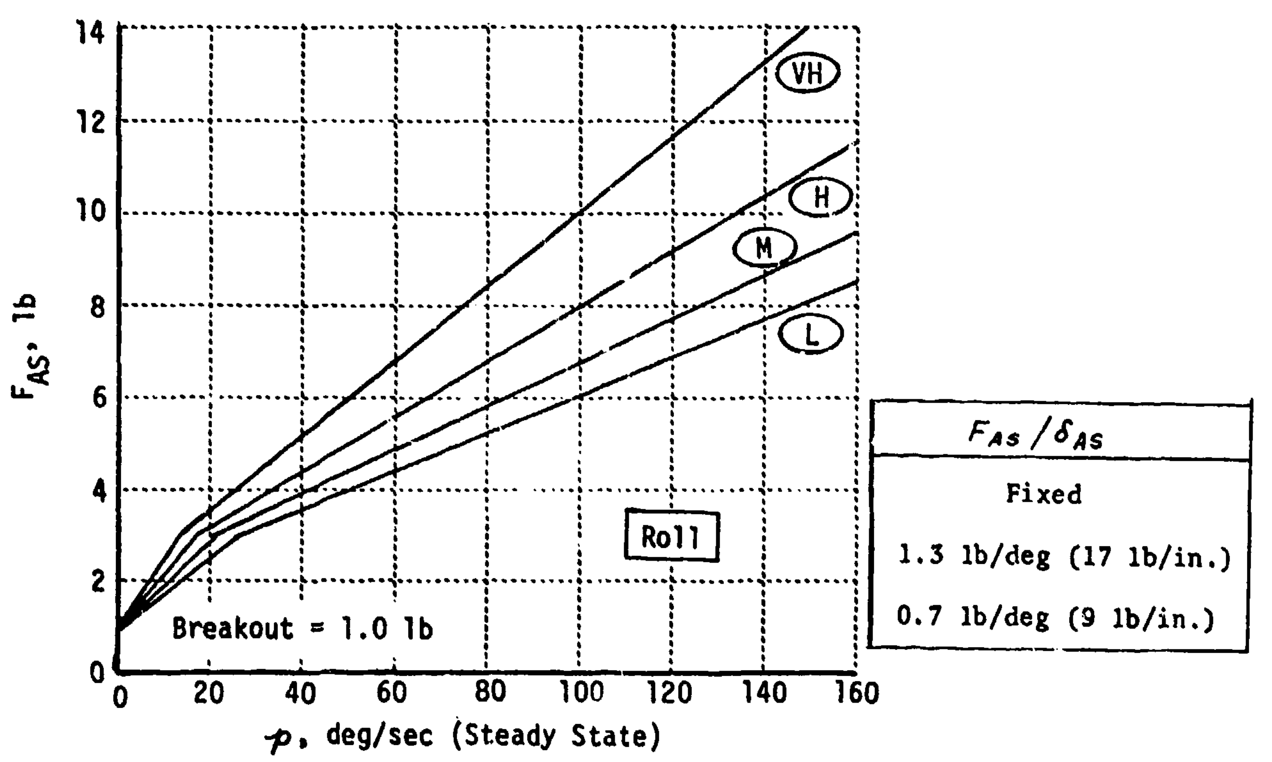
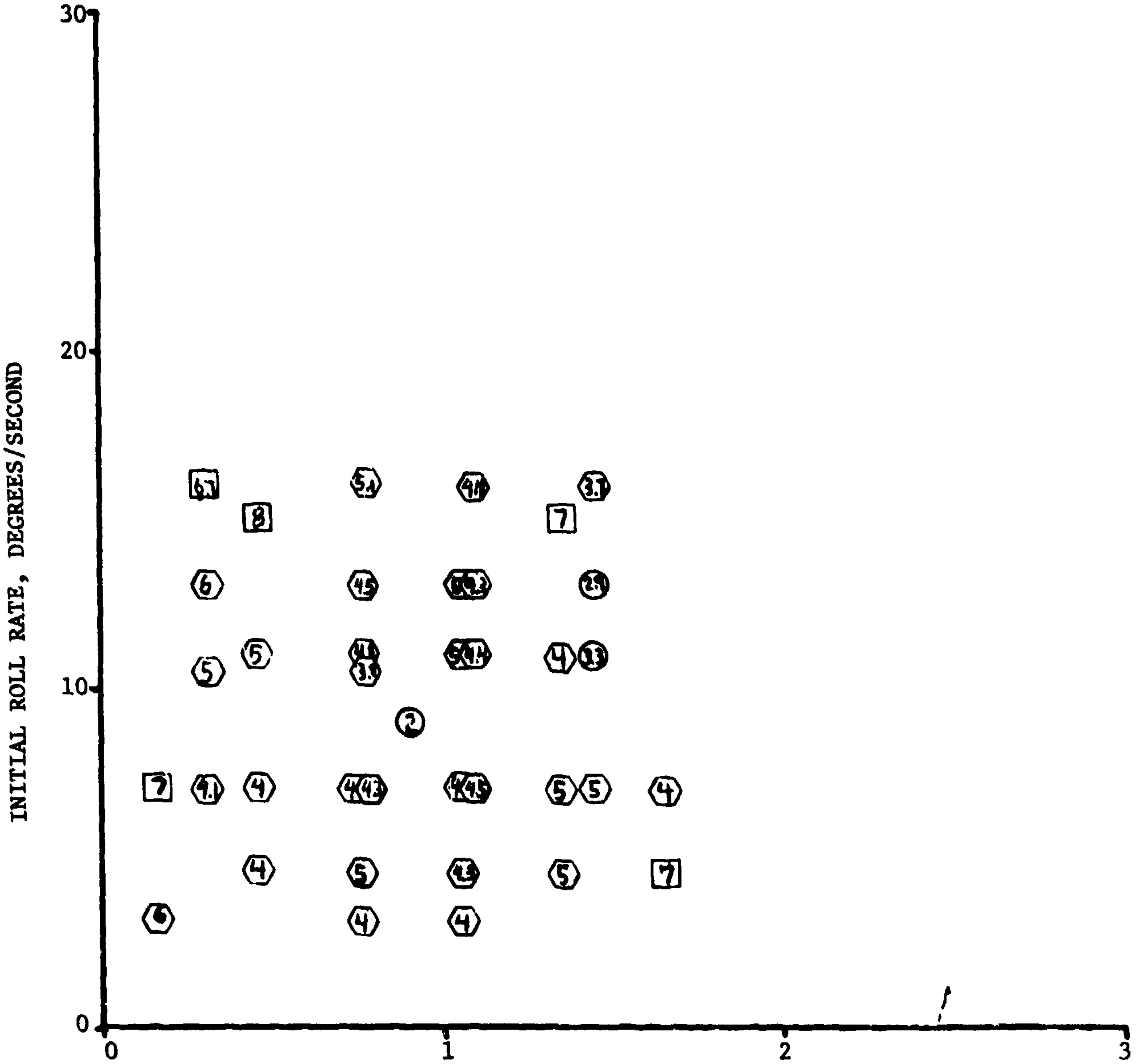


FIG 11: LATERAL CONFIGURATIONS EVALUATED IN
REFERENCE 1 (FIG FROM REF 1)



LATERAL STICK DEFLECTION-FORCE GRADIENT, DEG/LB
FIGURE 12: LATERAL MATRIX

with a longitudinal gradient of .0455 lb^{-1}, provided the "light" control force/response gains are used (5 lb/g initially, which is confirmed by References 5 and 6). On the JF-101A, a value of .0778 lb^{-1} (with .056 lb^{-1} longitudinally) was preferred, though performance was slightly better with lighter forces yielding a normalized lateral gradient of .0515 lb^{-1}. The preferred values from Reference 6 are .0418 lb^{-1} longitudinally and .0526 lb^{-1} laterally. All of these are shown graphically in Figure 13.

This evidence seems to point toward a pilot preference for a lateral normalized deflection/force gradient ranging from the same as to about 60% higher than the longitudinal normalized deflection/force gradient. Again, as in the pitch axis, pilots liked 1/2 lb breakout forces (Ref. 2).

The use of nonlinear roll response has been evaluated on the NT-33A projects conducted by students at AFTPS. All experiments except the spring 79 experiment used a halving of the force/response gradient above 3 to 4 lb absolute stick force. During the spring 1979 experiment (Ref. 6) gradients of 4:1 and 6:1 were also used. These gradient changes were evaluated as being too abrupt in their responses to a pilot input, in comparison with the 2:1 gradient change, and should be considered unacceptable.

Results from the NT-33A projects indicate that in roll response, as in pitch, the aircraft should be at the maximum response when the control stick reaches a stop. That is, the aircraft should be at maximum available or allowable roll rate at full side deflection of the stick. The use of "soft stops" is not recommended; stick stops should be unmistakably discernible to the pilot. This again leaves a requirement to define the minimum acceptable lateral stick travel.

Analogous to the preference for lower short-period frequencies in sidestick-controller aircraft is a preference for a roll mode time constant slightly higher (i.e., slower) than the minimum value tested. Reference 5 indicates that the preferred value may be around .35 seconds. A value of .3 seconds was used during the spring 1979 AFTPS student project (Ref. 6); results indicate no negative pilot comments concerning roll response.

F. <u>Trim Systems</u>.

The current trend is toward series trim systems where the geometric stick neutral (i.e., center) point remains constant. By contrast,

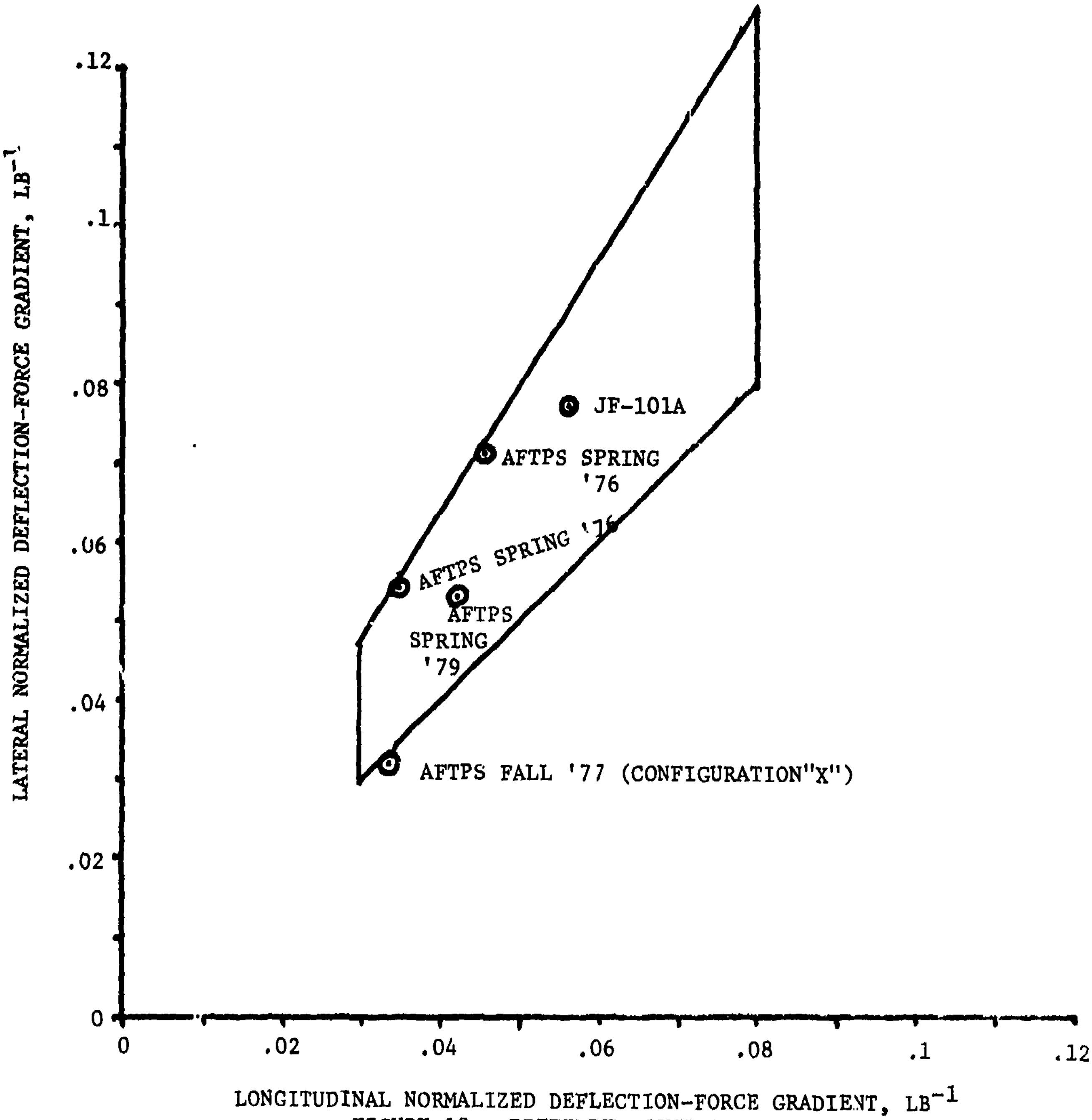


FIGURE 13: PREFERRED CONTROL HARMONY

requirements for constant normalized stick deflection/force gradients, constant lateral and longitudinal normalized gradient ratios and hard stick stops would tend to favor the use of parallel trim systems. In a parallel trim system the stick center position varies with trim setting. (For example, say a pilot were to place the aircraft in a 2g trim requiring 3 lb back pressure on the stick and correspondingly 1 1/2 degrees of back motion from the 1g neutral point. When he trims out the 3 lb force, the stick will still be 1 1/2 degrees aft of the 1g neutral point.) This preserves the recommended requirements independent of trim setting.

G. The Use of Prefilters.

A prefilter is a control element between the controller and the control surface actuator. Its purpose is to filter out higher-frequency pilot inputs, yielding a smoother command input to the aircraft. All AFTPS experiments were performed with a 16 rad/sec prefilter, except the spring 1978 experiment which evaluated other prefilter frequencies (Ref. 4). This reference indicates that given good deflection/force and response characteristics, pilots prefer the highest frequency prefilter available, i.e., the minimum amount of filtering. The handling qualities analysis work of Ralph Smith (see Ref. 26), however, indicates that pilot ratings will be improved if high frequency peaks in the amplitude response can be filtered out without adding phase lag. This matter has not been pursued further, and would be a candidate for future thought or work. The use of a "lower frequency" aircraft would need to be evaluated in terms of the total airplane system requirements and performance.

SECTION V

DESIGN GUIDANCE

Based on the data available at this time, it seems that it is possible to synthesize a good sidestick controller design for a fighter aircraft with a reasonable degree of confidence. The recommendations for the design follow.

a. Basic Aircraft

The aircraft would be acceptable with a lower short-period frequency than would be deduced from the current MIL-F-8785B requirements. The roll-mode time constant may have a minimum acceptable value in addition to the current MIL-F-8785B requirements. This may, however, apply only to maneuverable aircraft (i.e., fighters).

b. Neutral Position

The neutral position of the sidestick should be oriented so that in wings-level unaccelerated flight the pilot need never move his wrist further aft than 5-7° forward of vertical to command maximum permissible load factor, or further outboard than 5° right of vertical to command maximum roll rate to the right.

Available data would tend to support a neutral position of 10° to 17° forward of vertical and 8° to 12° left (inboard) of vertical, providing the constraints of the first point under this heading are not violated. A pilot adjustable armrest is absolutely mandatory, and its design can influence pilot acceptability as much as any other parameter.

c. Breakout Forces

Breakout forces should be no greater than 1 lb and no less than 1/2 lb.

d. Control-Stick-Mounted Function Switches or Buttons

Any switches, buttons, trim switches, etc., mounted on the control stick should have breakout forces no greater than 50% of those used for the control stick itself.

e. Control Stick Motion

Fixed sticks are satisfactory only for commanded pitch-down motions. The minimum recommended pitch-up deflection is 2° from neutral to full aft.

Lateral deflection limits should be consistent with longitudinal limits.

f. Longitudinal Force/Response Gradient

The initial longitudinal force/response gradient should be determined from the recommended region of Figure 9 of this report, given a known aircraft short-period frequency.

Nonlinear gradients are preferable with the final slope less than or equal to twice the initial slope.

g. Lateral Force/Response Gradient

Nonlinear gradients are acceptable if the final slope is less than or equal to twice the initial slope.

h. Longitudinal Deflection/Force Gradient

The aft longitudinal deflection/force gradient divided by the total available deflection from the neutral position to the full aft position should lie in the range of .03 lb^{-1} to .08 lb^{-1}, with the lower portion of the range being preferred.

The forward longitudinal deflection/force gradient may be as little as 1/9th the aft gradient based on Reference 14, though more symmetric gradients would be encouraged for larger stick deflection ranges.

i. Lateral Deflection/Force Gradients

The lateral deflection/force gradient divided by the total available deflection from the neutral position to the full left or right deflected position should lie in a range of 1 to 1.6 times the longitudinal normalized deflection/force gradient.

Symmetric left and right gradients through neutral are recommended, although we retain the possibility that lower maximum force and deflection to the right may be acceptable.

j. Stick Stops

Hard stops should be employed; i.e., full or maximum allowable airplane response should occur when the stick reaches maximum deflection for the appropriate command. These stops should be easily discernible to the pilot.

k. Trim Systems

Based on items (h, i and j) in this section, parallel trim systems are speculated as being most appropriate.

SECTION VI

IMPLICATIONS TO THE FLYING QUALITIES SPECIFICATION

Results given in the preceding Sections show that various requirements need to be evaluated for the impact of sidestick controllers. The current edition of the specification (Reference 24) does not contain any reference to sidestick controllers. The proposed MIL-F-8785C contains only minor references to them, so that all requirements are open for consideration.

A. Force and Deflection Limits.

The deflection limits discussed in the preceding sections may be considered candidates for the Level 1 boundaries. By contrast with existing requirements for wheels and center sticks, we now may need to consider an allowable range of neutral positions. Vertical to 12° inboard for roll, and vertical to 17° forward in pitch, are suggested ranges. It is not clear, however, that this is an item that needs specification as a flying qualities requirement. Maximum force and deflection limits could be set by anthropomorphic considerations. MIL-F-8785B currently sets a wheel throw limit for roll control, and could add analogous limits for sidesticks for both pitch and roll.

B. Pitch Response Characteristics.

The pitch results contain two separate factors, viz the selection of higher force with the higher short-period frequency and the apparent selection of a lower range of acceptable short-period frequencies for sidestick-controlled aircraft. The first of these factors is in line with prior data and could be correlated by a parameter such as pitch acceleration (or load factor) due to stick force. MIL-F-8785B contains limits for minimum stick force per load factor, but not recommended values.

The short-period parameter ω_n^2/n_α is approximately equivalent to $\left|\frac{\ddot{\theta}}{F_s}\right|_{max} \Big/ \left|\left(\frac{n}{F_s}\right)\right|_{ss}$, the ratio of initial pitch acceleration to final steady state normal acceleration response for a step command, independent of the type of controller. This parameter is affected by the second of the results listed. If the indication of a different choice of short-period frequencies for sidestick is valid (i.e., verified by further data), then this implies revision of the specification is needed. On a first level, this revision could be accomplished by empirical correlation of new values for ω_n^2 / n_α.

Sufficient data would need to be accumulated to give consistent, substantiated boundaries.

We may also speculate on a more fundamental level on the cause of the indicated trend. Consider again the meaning of parameter ω_n^2/n_α specified in MIL-F-8785B. Now the data being evaluated is for an elevated-g tracking task, where the steady-state response to a control input may not have much meaning since the pilot is continuously adding control inputs. This is consistent with the conjecture put forward in Section III of this report, i.e., the inertia of the pilot's arm and controller is a factor in the response. This would only be true in a high-frequency, highly dynamic situation, probably Class IV (fighter) configurations in Category A Flight Phases (e.g. air combat or weapon delivery). A limited amount of data is also available in Reference 28. These ground-based simulation results for a sidestick-controlled Class III (transport) aircraft in landing approach (Category C) show good agreement with MIL-F-8785B values for ω_n^2/n_α. These flight phase conditions would not be expected to impose any requirement for abrupt maneuvering, supporting the thesis that we are attempting to explain an effect of maneuverability.

Reference 29 proposes the existence of a "flying qualities nerve". The parameter $\sigma_{\dot{\beta}_q}$ is proposed as the output of this nerve in response to pitch rate. The hypothesis suggests we are searching for requirements on a parameter such as $\ddot{\theta}/\sigma_{\beta_q}$. If such a transfer function existed, it would contain "physical lags" such as the effect of arm inertia, in addition to the parameters normally included in pilot models. This extension is pure speculation. It is concluded, however, that the current short-period frequency requirements in MIL-F-8785B may need revising for sidestick controllers in Class IV aircraft in Category A Flight Phases. Sufficient data is not currently available to accomplish this.

C. Roll Response Characteristics.

The results on roll mode time constant imply an effect similar to that discussed for short-period characteristics. Heavier forces are selected with the more sensitive configuration having a lower roll mode time constant. In addition, a definite preference was stated for the medium roll mode time constant of 0.4 secs, in Reference 5, although all the values tested (0.2, 0.4 and 0.9 seconds) are within the Level 1 requirement of MIL-F-8785B.

Reference 1 on the other hand shows pilot ratings of 3 for both 0.2 and 1 second. The Level 1 requirement in MIL-F-8785B is only for a maximum value of 1.0 second, whereas the results imply that a minimum value may also be appropriate. The requirement for a minimum roll mode time constant is probably a more general one which has not previously been a problem in practice. Now with an electric sidestick controller and fly-by-wire control system these low time constants can be achieved in the response to stick input, thus we need to consider this as a specification item.

SECTION VII

CONCLUSIONS AND RECOMMENDATIONS

This report presents previously unpublished data and attempts to correlate it with existing data on sidestick controllers as applied to aircraft flying qualities. The objectives were to formulate design guidance and to discuss possible impacts on the existing military flying qualities specification. The ideas of normalized deflection/response gradients and optimal values for these gradients have been presented along with data and rationale to support the ideas. A possible interaction between the longitudinal force/response gradient and the aircraft short-period frequency has been presented. Finally, recommendations have been made concerning the stick neutral position and allowable deflections based on available data.

It is stated as a conclusion of this report that sufficient data exists at this time to form design guidelines and to suggest that revision of the current flying qualities specification may be needed. For design guidance recommendations, the reader is referred to Section V of this report. Possible specification revisions are discussed in Section VI. It is felt that there is still insufficient data to substantiate any revisions at this time.

In the data reviewed for this report, five potential areas for future research became apparent. They are:

1. Further exploration of the interaction between short-period frequency and controller force/response characteristics,

2. Further research to validate the concept of normalized deflection/force gradients and to define acceptable/unacceptable ranges of lateral to longitudinal gradient ratio,

3. The use of nonorthogonal or skewed sidestick axes,

4. Optimizing the neutral position of the controller,

and 5. The use of nonsymmetric roll deflection/response gradients.

One comment on the relationship of items 2, 4 and 5 is necessary here. In light of the apparent preference for a lateral to longitudinal normalized gradient ratio of between 1:1 and 1.6:1 it appears that nonsymmetric roll

gradients would be excluded. It is possible that the disadvantages (if any) of this can be overcome by properly positioning the stick such that the pilot need never move his wrist further than around 5^{o} outboard of vertical. This would seem to be preferable to using nonsymmetric roll deflection/response gradients.

APPENDIX A

A SAMPLE DESIGN PROBLEM

In this section, a sample design for fighter application will be formulated. Rationale will be given for the various choices.

First, for the critical flight condition it will be assumed that the short-period frequency is around 3.5 radians per second and the roll mode time constant is .3 seconds. This is in the recommended area from the AFTPS experiments, as discussed in Sections IV-D and E of this report.

A base-pivoted two-axis sidestick will be used. A pilot-adjustable armrest will be included in the installation. The neutral position will be chosen to be 15° forward and 10° left of vertical. These numbers are approximately in the center of the preferred region. Breakout forces of 0.8 lbs will be used, with control switch breakout forces of 0.4 lbs. These choices are in accordance with the discussion in Section IV-B.

The stick force/airplane response relationship is defined by the choice of certain basic parameters. The force/response gradient through zero should be appropriate to the tracking task and the maximum force should be consistent with the maximum response. If a break in the slope is required then this should be at a response level just above what is required in normal tracking, although it is expressed herein in terms of a break force as being a more convenient design parameter. Also, although this example is written in terms of a critical flight condition, an actual design would have to be evaluated over the whole flight envelope and tailored as necessary.

From Figure 9 of this report, the recommended initial pitch force/response gradient for aft deflections is found. A value of 7 pounds per "g" is selected. As discussed in Section IV-C, the gradient will be halved (to 3.5 lb/g) at 4 lb (absolute) stick force. This variation is presented graphically in Figure 14. A 28.5 pound pull force will command 9 g's, which is assumed to be the design load limit.

Now a requirement for a longitudinal normalized deflection-force gradient of .03 lb^{-1} to .08 lb^{-1} is imposed. Based on the discussion in Section IV-C, a value of 0.035 lb^{-1} is chosen. Also, at this time, an aft deflection limit of 10° (from neutral) is chosen. Multiplying these two values and inverting yields the aft longitudinal force/deflection gradient of approximately 2.86 lb/deg.

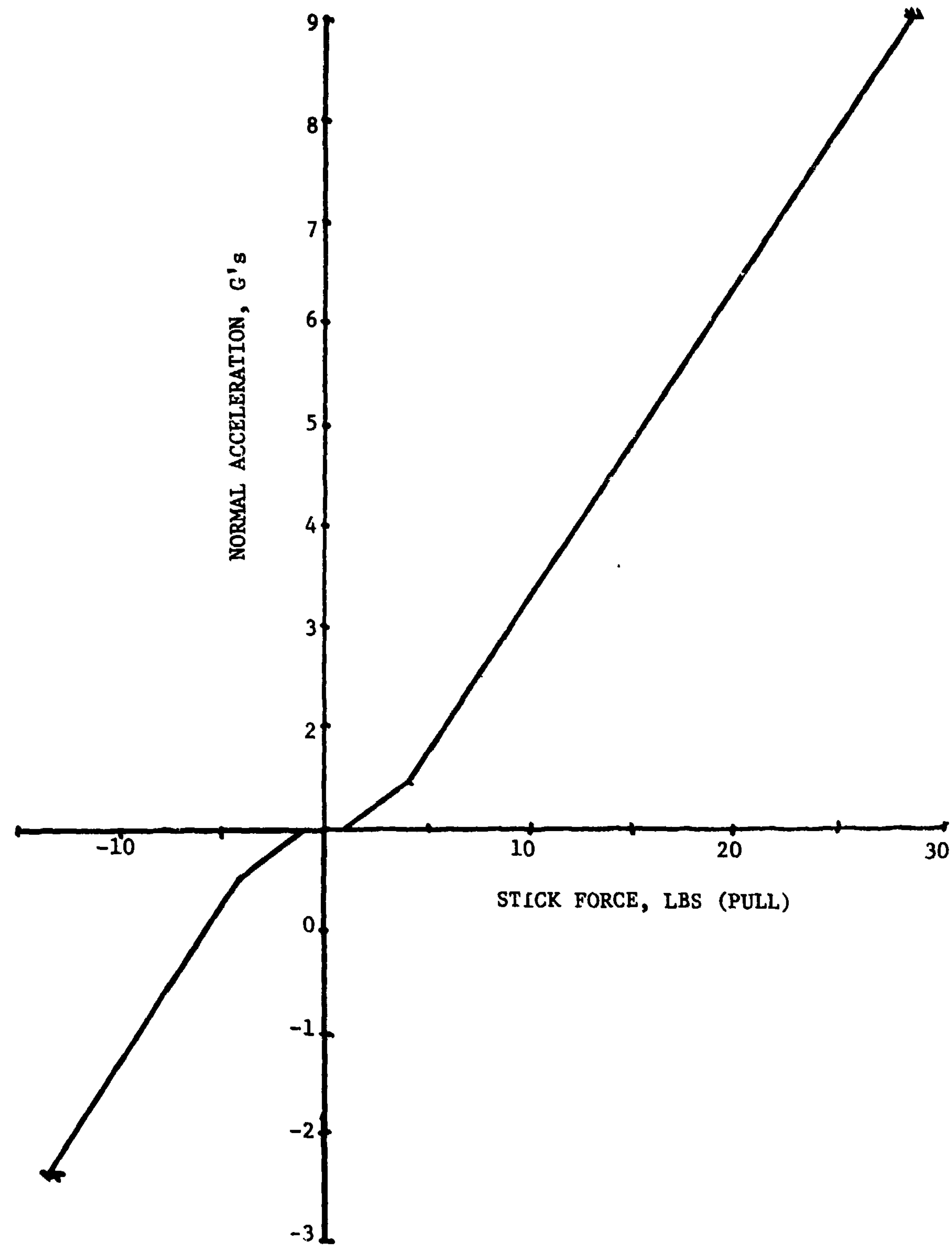


FIGURE 14: PITCH RESPONSE

The forward deflection limit has not yet been discussed. As discussed in Section IV-C of this report, the forward deflection limit need not be identical to the aft limits. The same pitch force/response gradient will be maintained by choice, as well as the same normalized deflection/force gradient. A limit of -2.6 g's is used, and the resulting force at this limit is 14.25 pounds. The resulting deflection limit is 4.97 degrees; 5 degrees will be used. This is also shown on Figure 14.

In accordance with the discussion in Section IV-E, a lateral normalized deflection/force gradient 30% higher than the longitudinal normalized force/deflection gradient is chosen. The resulting value is .0456 lb^{-1}. Deflection limits of $\pm 10^{\circ}$ are chosen in order to be consistent with the longitudinal limits. This results in a gradient of approximately 2.2 pounds per degree of lateral stick deflection.

Assuming the aircraft has a maximum steady roll rate of 180° second, working backwards under the constraints of 0.8 lb breakout forces and a halving of the force/response gradient at 3 pounds stick force yields Figure 15. The force/response gradients are approximately 3.6 degrees per second per pound initially, and approximately 7.2 degrees per second per pound beyond the break point.

As discussed in Section IV-F, a parallel trim system is suggested.

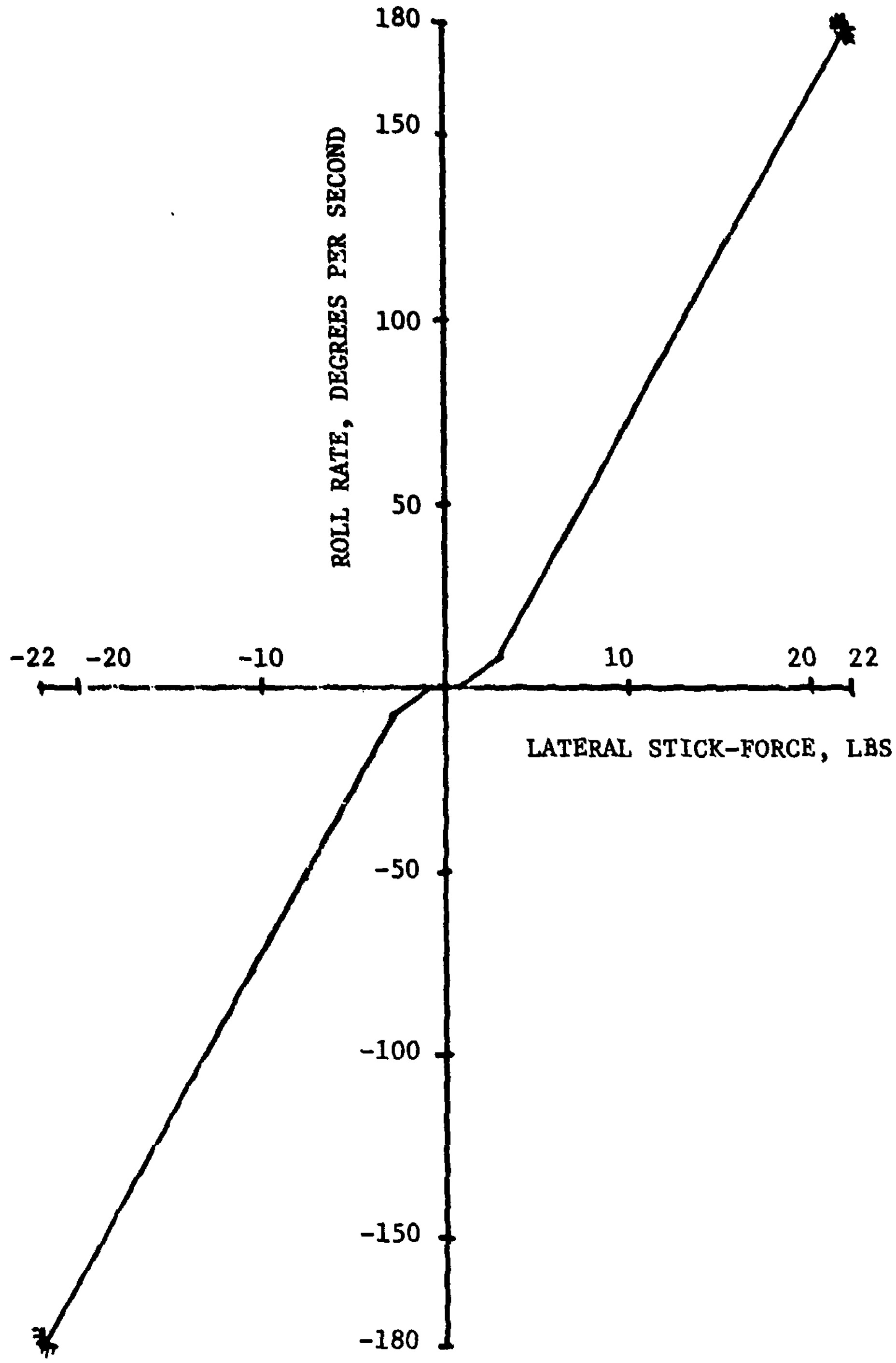


FIGURE 15: ROLL RESPONSE

APPENDIX B

TECHNICAL RESULTS AND DISCUSSION FROM USAF TEST PILOT SCHOOL LETTER REPORT - 1 July 1977 "Limited Flight Evaluation of Sidestick Controller Force/Deflection Characteristics on Aircraft Handling Qualities" by William M. Cima, Lieutenant, USN; Armand Jacob, Captain, FAF; Thomas J. LeBeau, Captain, USAF; Charles M. Miller, Captain, USAF and Jack T. Stebe, Captain, USAF.

ABSTRACT

A limited investigation of the effect of sidestick controller longitudinal and lateral force and deflection characteristics upon the pilot evaluation of aircraft handling qualities in Category A and C tasks was conducted. Twenty-three flights were flown in the NT-33A, USAF S/N 51-4120 from 13 May 1977 to 3 June 1977 at the USAF Flight Test Center, Edwards AFB, California. Data presented consists of Cooper-Harper pilot ratings and comments on each control configuration. These data can be used in specifying requirements and design criteria for Class IV aircraft with sidestick controllers. Pilots preferred large control stick motion with light control force gradients for the air-to-air tracking task. Aircraft lateral-directional characteristics detracted from the pilot's ability to evaluate lateral control effectiveness and control harmony. The approach tracking task did not enable the pilots to discriminate between control configurations. Insufficient data were obtained on the landing task to properly define the areas of good configurations.

INTRODUCTION

This report[2] presents the results of a limited flight test investigation of the effect of sidestick controller longitudinal and lateral force and deflection characteristics upon the pilot evaluation of aircraft handling qualities in Flight Phase Category A and C tasks.[21]

This test was similar to a previous test performed by Calspan for the Flight Dynamics Laboratory, Flight Investigation of Fighter Sidestick Force-Deflection Characteristics, AFFDL-TR-75-39.[1] During the tests of Calspan, the pilots evaluated the air-to-air handling qualities while performing operational tracking maneuvers. However, during this test at the Air Force Flight Test Center, a tracking task developed and reported by Mr. Thomas R. Twisdale[22] was used to evaluate air-to-air handling qualities. The Twisdale procedure incorporated structured tracking maneuvers and did not permit use of the rudders by the evaluation pilot during tracking. Furthermore, a slight amount of proverse yaw was added which increased the aircraft's suitability for the Twisdale tracking task.

TEST METHOD

Reference 1 describes the airplane and the basic dynamics are given in Table II. Configurations to be evaluated for each mission were selected from Table III with the stick force and deflection characteristics shown in Figures 16-19. These configurations were arranged so that no two similar configurations were evaluated consecutively. At no time during the test program were the evaluation pilots exposed to the previously collected data or aware of configurations tested.

Air-to-air and air-to-ground tracking tasks were used to evaluate the sidestick controller configuration in Flight Phase Category A. Instrument approach and landing tasks were used to evaluate sidestick controller configurations in Flight Phase Category C.

Air-to-air tracking tasks were started with the NT-33A approximately 2000 feet behind the target aircraft. The pipper aim point was the center of the target fuselage at the wing/fuselage junction. The specific tracking task for each configuration consisted of the following:

1. Two 280 KIAS 2 g turns in opposite directions for a heading change of approximately 180 degrees.

2. Two wind-up turns in opposite directions maintaining 280 KIAS from 1 to 3.5 g at an onset rate of 0.1 g/second.

TABLE II

DYNAMIC CHARACTERISTICS OF TEST AIRCRAFT

Parameter		Flight Phase Category A Dynamics	Flight Phase Category C Dynamics
n_z/α	g/rad	33	7
ω_{sp}	rad/sec	5.0	2.2
ζ_{sp}		0.6	0.5
ω_p	rad/sec	.09	.15
ζ_p		.05	.05
τ_R	sec	.2	0.5
τ_s	sec	∞	∞
ω_d	rad/sec	3.2	1.2
ζ_d		0.4	0.25
$\|\phi/\beta\|_d$		0.5	3

NOTE: These characteristics are based upon 300 KIAS at 12,000 feet for Category A Flight Phase and upon 145 KIAS at 4,000 feet for Category C Flight Phase. Proverse Yaw: $N\delta_a/L\delta_a$ 0.016

TABLE III

CATEGORY A CONTROL CONFIGURATIONS*

Config. No. See Fig 18	F_{es}/n_z See Fig 16	δ_{es}/F_{es} deg/lb	F_{as}/P See Fig 17	δ_{as}/F_{as} (deg/lb)	Remarks
1	very light	.2	very light	.3	Alternate Config
2	light	.2	very light	.3	
3	medium	.2	medium	.3	
4	heavy	.2	heavy	.3	
5	very light	.5	very light	.77	
6	light	.5	light	.77	
7	medium	.5	medium	.77	
8	heavy	.5	heavy	.77	
9	very light	.7	very light	1.08	
10	light	.7	light	1.08	
11	medium	.7	medium	1.08	
12	heavy	.7	heavy	1.08	
13	very light	.91	very light	1.43	Alternate Config.
14	light	.91	light	1.43	Alternate Config.
15	medium	.91	medium	1.43	Alternate Config.
16	heavy	.91	heavy	1.43	Alternate Config.

*When pilot comments indicated that control harmony detracted from the rating given any of the above configurations, variations in control harmony were evaluated. This was accomplished by selecting additional control configurations. The longitudinal stick force per g and stick deflection per unit force for the control configurations being investigated were held constant. The lateral stick force per unit roll rate and the lateral stick deflection per unit force were varied independently in accordance with values shown in Figure 16 and Table III respectively.

CATEGORY C CONTROL CONFIGURATIONS

Config. No. See Fig 19	F_{es}/N_z See Fig 17	δ_{es}/F_{es} (deg/lb)	F_{as}/P See Fig 16	δ_{as}/F_{as} (deg/lb)	Remarks
17	light	0.2	light	0.3	
18	medium	0.2	medium	0.3	
19	light	0.5	light	0.3	
20	medium	0.5	medium	0.77	
24	medium	0.91	medium	.143	
23	light	0.91	light	1.43	Alternate Config.
21	light	0.7	light	1.08	Alternate Config.
22	medium	0.7	medium	1.08	Alternate Config.

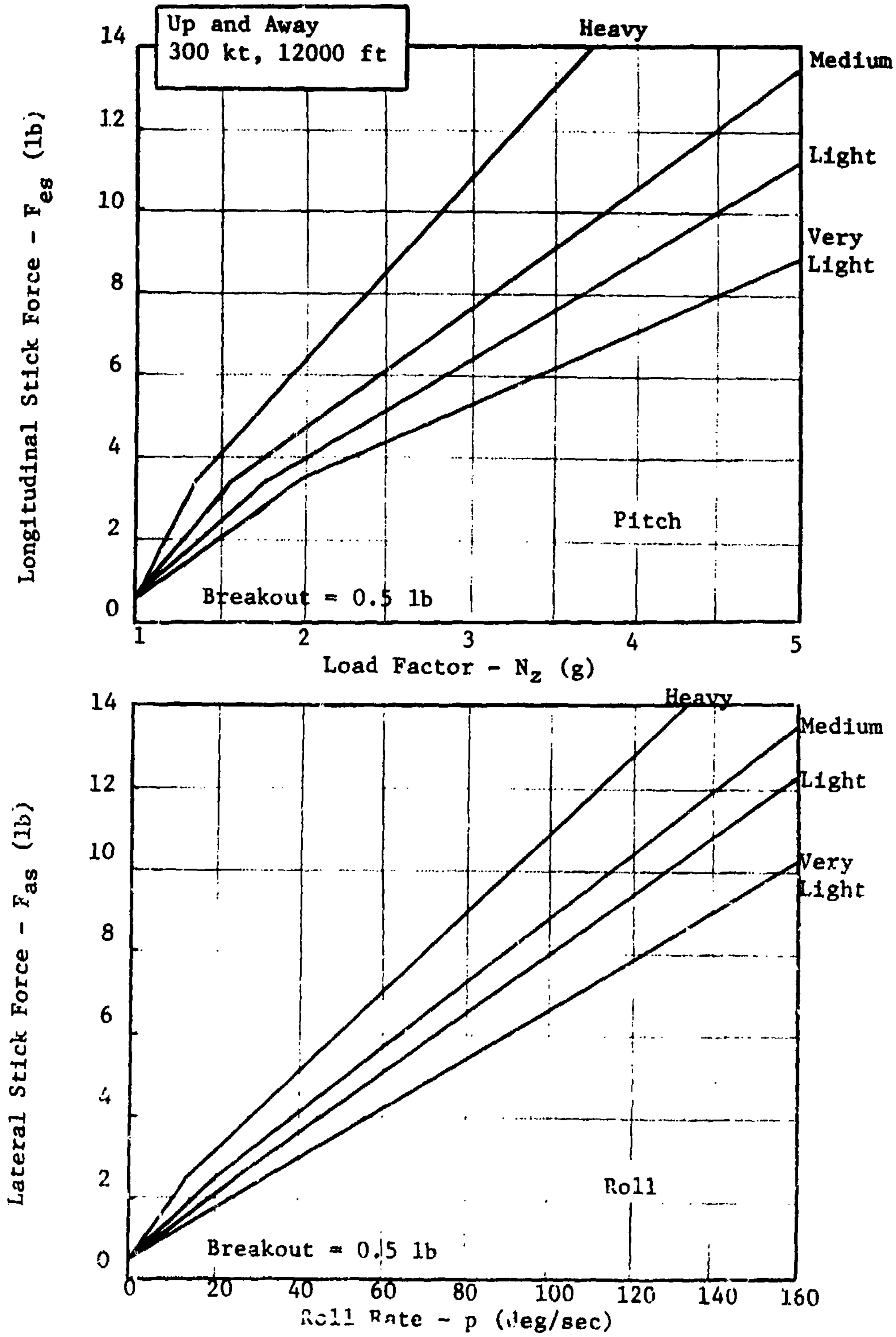


FIGURE 16 Control Force/Response Gains, Flight Phase Category A

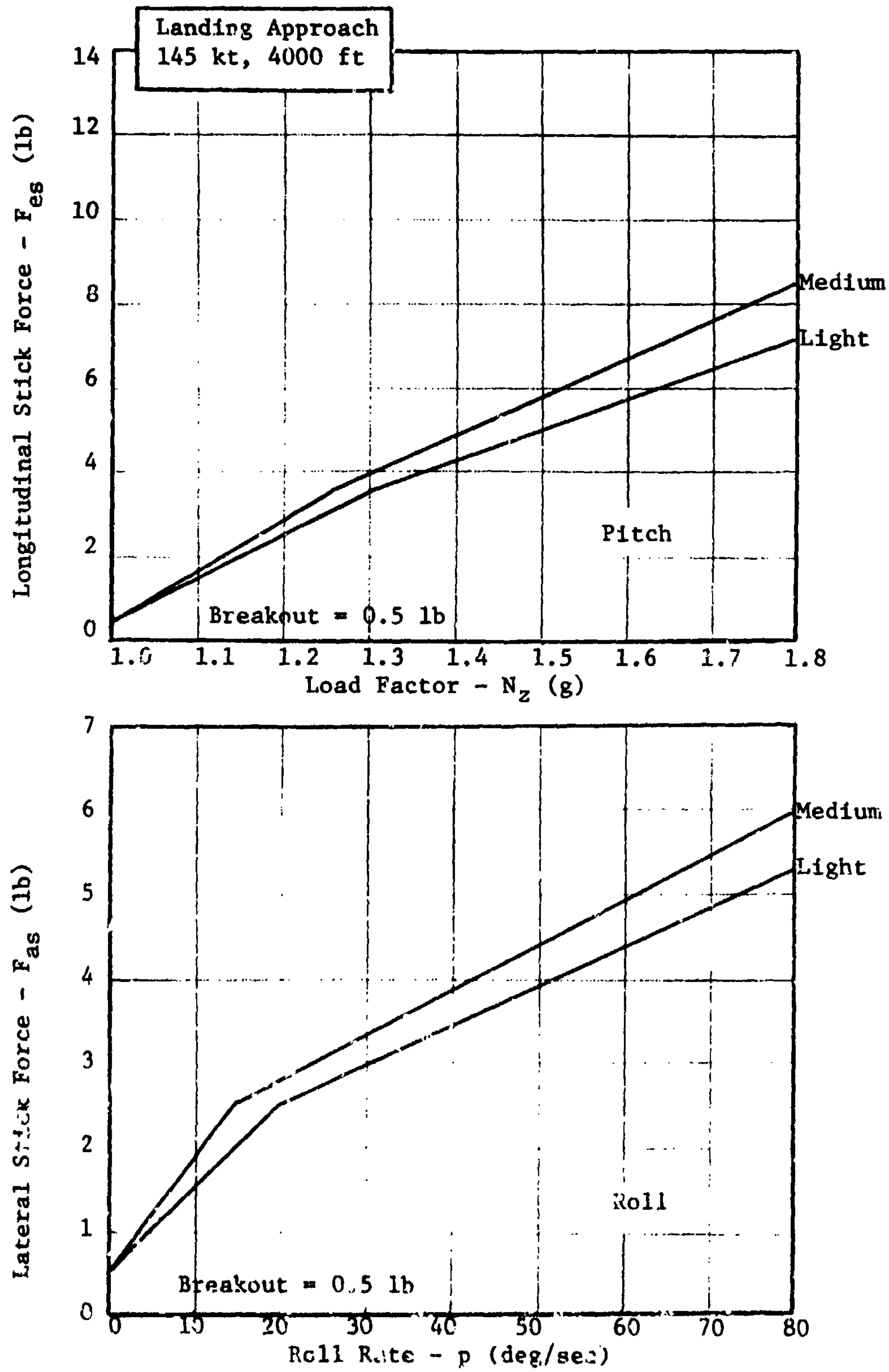


FIGURE 17 Control Force/Response Gains, Flight Phase Category C

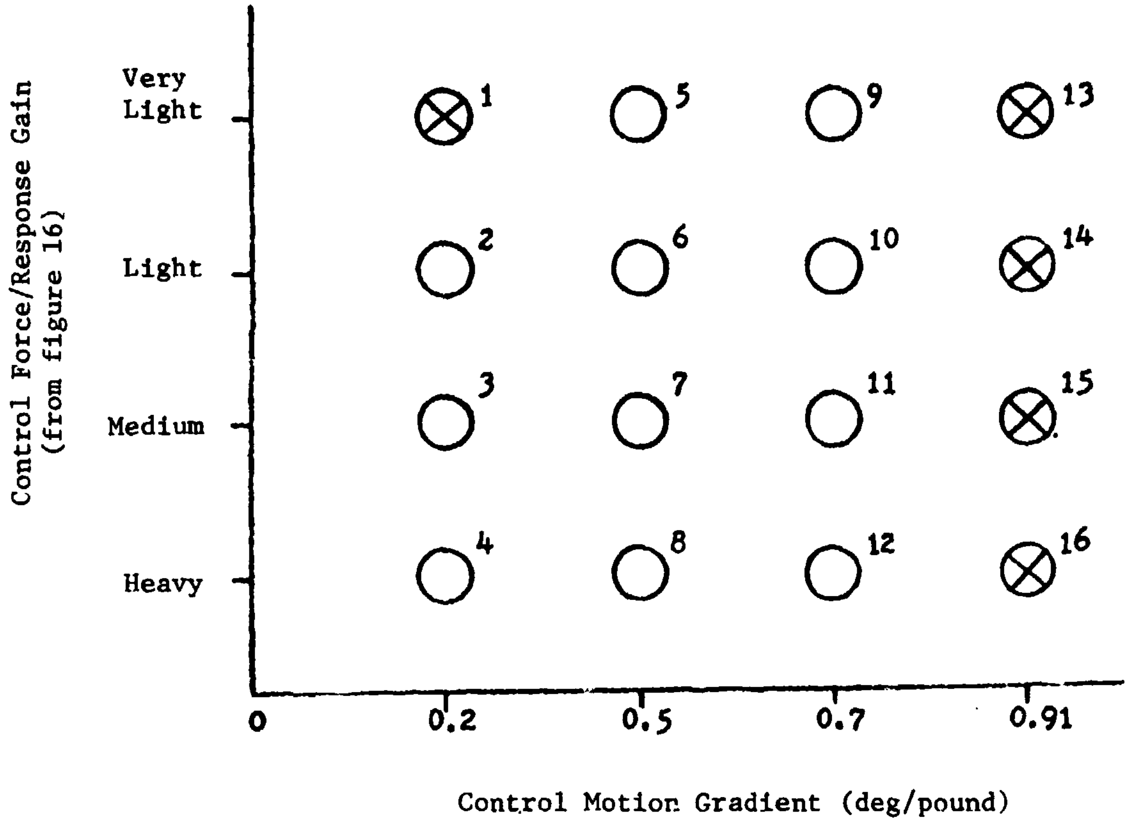


FIGURE 18 CONTROL CONFIGURATION FOR CATEGORY A TASKS

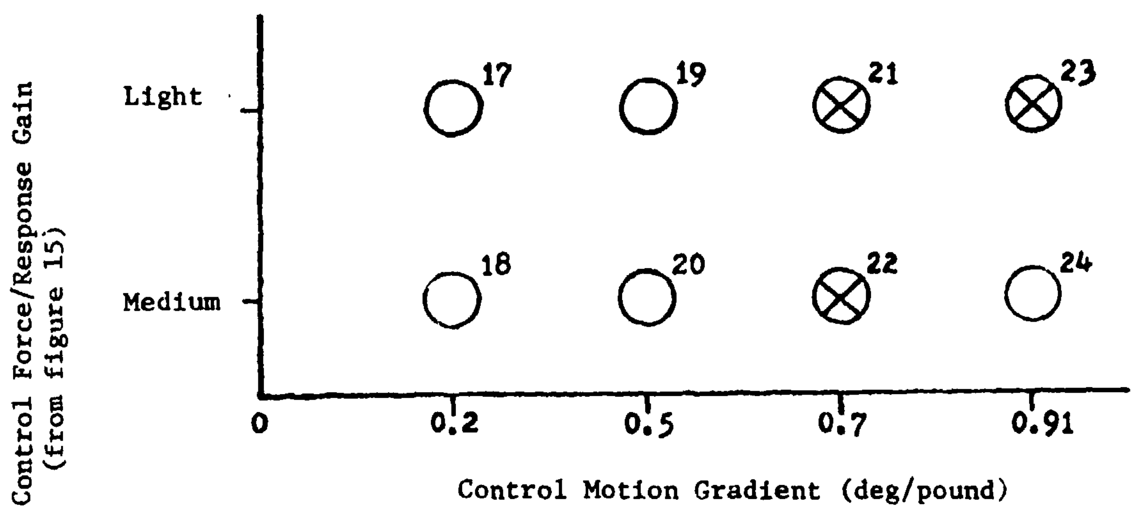


FIGURE 19 CONTROL CONFIGURATION FOR CATEGORY C TASKS

The above sequence was accomplished for each flight control configuration at least once, but repeated as often as the evaluation pilot required. The evaluation pilot then completed the inflight debriefing and the NT-33A control system was reconfigured.

For the air-to-ground tracking task, the evaluation pilot used a designated target within R2508, Edwards AFB restricted area. The air-to-ground bombing pattern is depicted in Figure 20 and tracking techniques described in Reference 9 were used. At the release altitude of 3,000 feet AGL a pull-out employing 4 g in 2 seconds and a climb to downwind were made. The above sequence was repeated as necessary for each of the control system configurations. Prior to base turn the evaluation pilot completed the inflight debriefing.

For the approach and landing task, the published ILS approach to Edwards AFB Runway 22 was flown with the evaluation pilot making an aggressive effort to stay on course and glide slope. At 200 feet AGL, the evaluation pilot transitioned to outside references to complete a touch and go landing. When established on downwind, the evaluation pilot completed the inflight debriefing. The aircraft was flown at 140 KIAS with landing gear and speed brakes extended and flaps at 30 degrees.

DATA REDUCTION

Pilot comments were summarized on a flight-by-flight basis according to each task evaluated. These summaries were reviewed and condensed to those comments that appeared to best typify each configuration and task combination.

Individual pilot Cooper-Harper ratings for each configuration and task combination were collated. No recognized statistical method existed to summarize pilot ratings. Therefore, several different methods were used towards this end. These methods consisted of the following:

1. Determining the average rating for each control configuration.

2. Obtaining the median rating for each control configuration.

3. Determining the average pilot rating for each of the three pilots over each control configuration. The average and median of these three averages were then determined.

4. Obtaining the median pilot rating for each of the three pilots over each control configuration. From these three median ratings, the average and median were then determined.

5. Calculating the standard deviations of all pilot ratings for each control configuration.

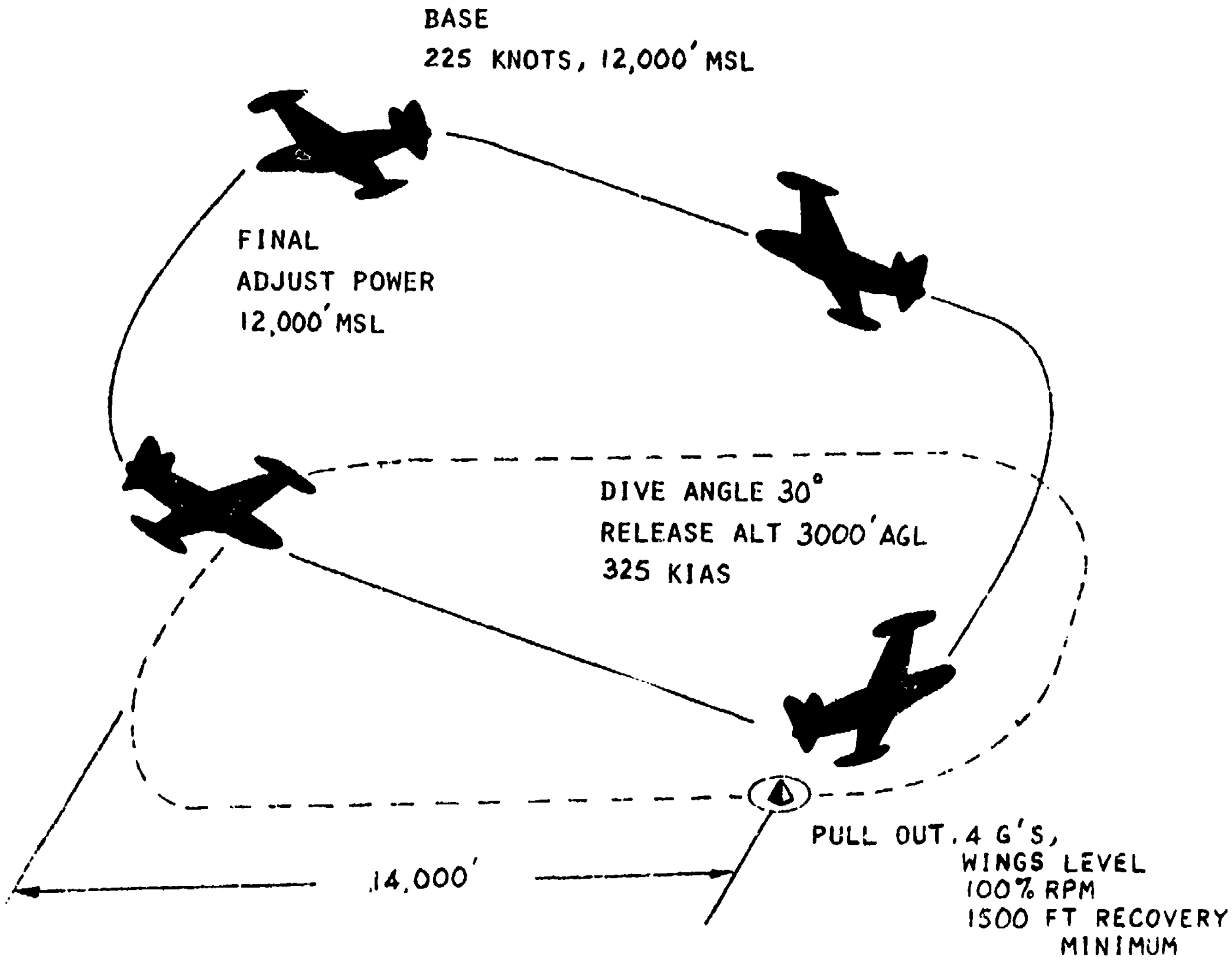


FIGURE 20. DIVE BOMB PATTERN

TEST RESULTS

Data were gathered and reduced for the air-to-air, air-to-ground and approach and landing tasks. Control harmony and the effect of breakout force on pilot ratings were investigated for selected air-to-air control configurations. Pilot background questionnaires are presented in Table IV.

The results of the air-to-air tracking tasks are presented in Figure 21: representative pilot comments for each control configuration are shown in Figure 22. The matrix of control configurations was divided into four areas based on relative performance. Although the Cooper-Harper ratings were treated with a variety of statistical reduction techniques, as shown in Figures 23 through 31, each technique have essentially the same area boundaries. Figures 25 and 29 show good correlation in ratings among pilots. Figure 32 shows the standard deviation for the ratings for each configuration to be approximately one. These data should be used in specifying requirements and design criteria for Class IV aircraft with sidestick controllers.

In general, pilots preferred increased control stick motion with decreased control force gradients and decreased control stick motion with increased control force gradients. Control configurations in area I of Figure 21 yielded the best results, both in pilot ratings and comments. Pilots indicated that control motions were noticeably large but not uncomfortable. Area I configurations were on the edge of the test matrix; thus, the extent of this area was not determined. Additional testing should be accomplished to completely define area I.

Area II configurations were found to be good, but slightly inferior to area I configurations. Pilot comments indicated that the stick forces for configuration 4 were tiring and uncomfortable. Though the boundaries were not completely determined, these comments imply that area II would probably not continue with heavier force gradients.

Area IV configurations were rated the poorest. They were characterized by longitudinal and lateral sensitivity or, in the case of configuration 16, aircraft sluggishness.

Area II includes all of the remaining control configurations. Note that with medium control stick motion, the control force gradient selected had essentially no effect on pilot ratings. However, pilot comments show a trend from oversensitivity to sluggishness as the control force gradient increased from very light to heavy.

The effect of breakout force on pilot ratings was investigated by increasing the breakout force to one pound for control configurations 7 and 11. Figure 33 shows that pilot ratings were worse for configuration 7 and essentially the same for configuration 11 as compared to ratings

TABLE IV

EVALUATION PILOT QUESTIONNAIRE

Personal Data
NAME Stebe, J.T. (Pilot A) RANK Capt SERVICE USAF
AGE 33 TOTAL FLYING TIME 3000 Hours

Detailed Flying Time Breakdown
(List most recent aircraft first)

AIRCRAFT	TIME (hrs)
U-2	500
T-33	450
B-66	275
T-38	1775

Approximate Total Number of Air-to-Air Sorties	0
Approximate Total Number of Air-to-Ground Sorties	0
Approximate Total Number of Aerial Refuelings	100
Approximate Total Number of ILS Approaches	150

Personal Data
NAME LeBeau, T.J. (Pilot B) RANK Capt SERVICE USAF
AGE 33 TOTAL FLYING TIME 1500 Hours

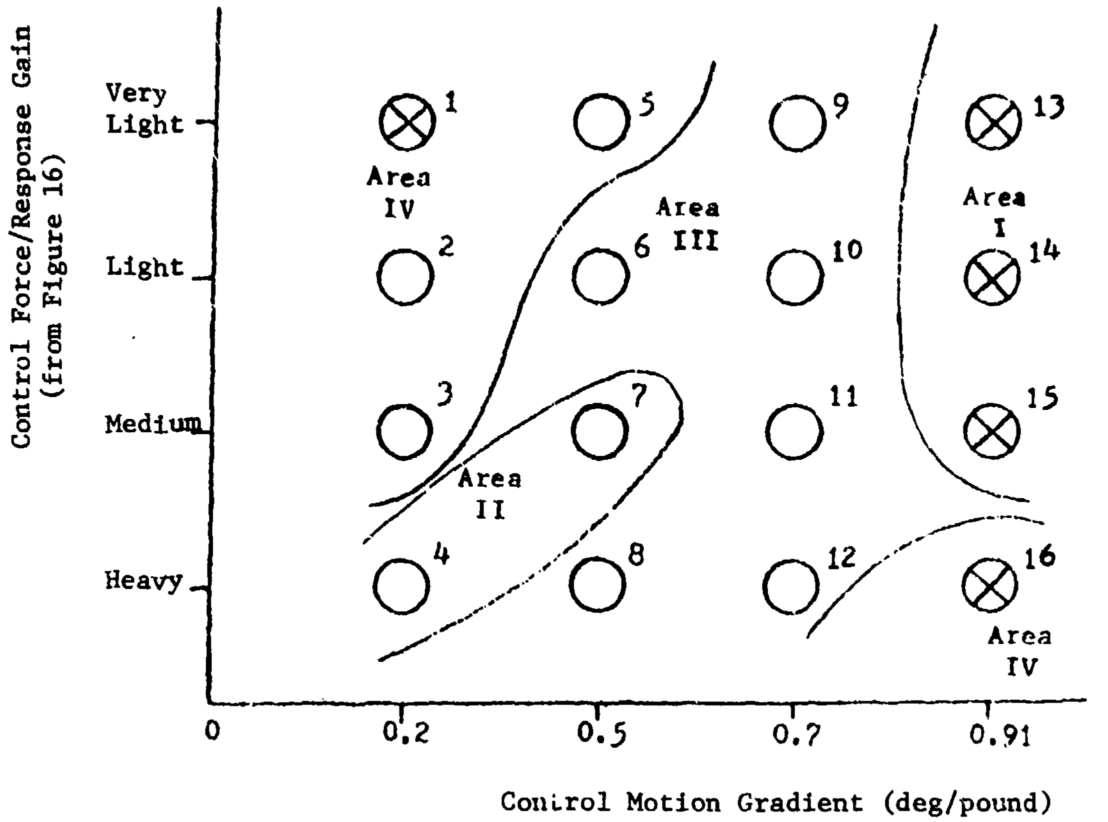
AIRCRAFT	TIME (hrs)
RF-4C	27
T-38A	61
B-52G/D	1170

Approximate Total Number of Air-to-Air Sorties	0
Approximate Total Number of Air-to-Ground Sorties	0
Approximate Total Number of Aerial Refuelings	80
Approximate Total Number of ILS Approaches	200

Personal Data
NAME Cima, W.M. (Pilot C) RANK Lt SERVICE USN
AGE 30 TOTAL FLYING TIME 1100 Hours

AIRCRAFT	TIME (hrs)
T-38A	60
RF-4C	25
F4J	700

Approximate Total Number of Air-to-Air Sorties	300
Approximate Total Number of Air-to-Ground Sorties	100
Approximate Total Number of Aerial Refuelings	200
Approximate Total Number of ILS Approaches	200



NOTE:		
	Average Cooper-Harper rating in Area I:	2.9-3.7
	Average Cooper-Harper rating in Area II:	3.8-4.1
	Average Cooper-Harper rating in Area III:	4.2-4.9
	Average Cooper-Harper rating in Area IV:	5.0-6.7

Figure 21. Areas of Control Configuration Relative Performance

Control Force/Response Gain (from Figure 16)	0.2	0.5	0.7	0.91
Very Light	1 Pitch extremely sensitive. Lateral fair. Avg of CH 6.7	5 Pitch and lateral both a little too sensitive. Avg of CH 5.1	9 Pitch and lateral are both too sensitive. Avg of CH 4.4	13 No pitch bobble tendency but imprecise position-ing. Avg of CH 3.7
Light	2 Pitch too sensitive. Lateral wandering and sensitive. Avg of CH 6.0	6 Slight pitch bobble. Better at higher g's. Lateral sluggish (cont. harmony). Avg of CH 4.5	10 Pitch a little sensitive. Lateral bobble. Avg of CH 4.3	14 Pitch and lateral steady and respon-sive. Motion notice-ably large. Avg of CH 2.9
Medium	3 Pitch a little sensitive. Lateral slow to respond. Avg of CH 5.0	7 Pitch steady once on tgt. Lateral forces high (cont. harmony) Avg of CH 3.85	11 Very slight pitch bobble tendency, but good. Large lateral corrections difficult Forces high & bobble Avg of CH 4.4	15 Motion noticeably large. No pitch bobble, slightly sluggish. Avg of CH 3.3
Heavy	4 Pitch very stable at higher g's, but forces tiring. Avg of CH 4.1	8 Pitch steady but forces too heavy. Lateral forces to heavy. Tiring. Avg of CH 4.3	12 A/C sluggish but stable. Forces heavy. Avg of CH 4.5	16 A/C very sluggish and forces uncom-fortable. Avg of CH 5.0

Control Motion Gradient (deg/pound)

Figure 22 Pilot Comments for Air-to-Air Tasks with Standard Harmony

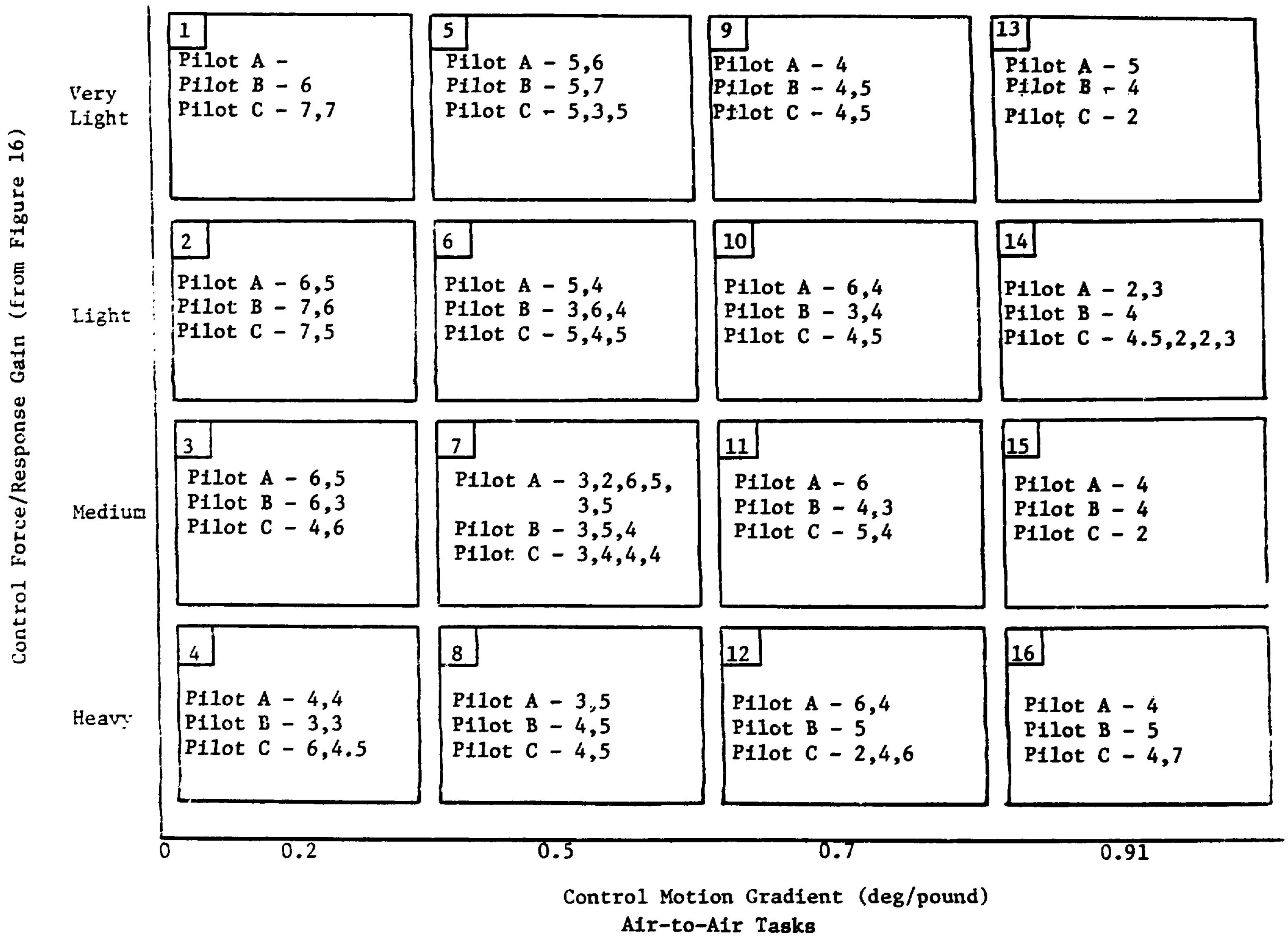


Figure 23 Pilot Ratings with Standard Control Harmony

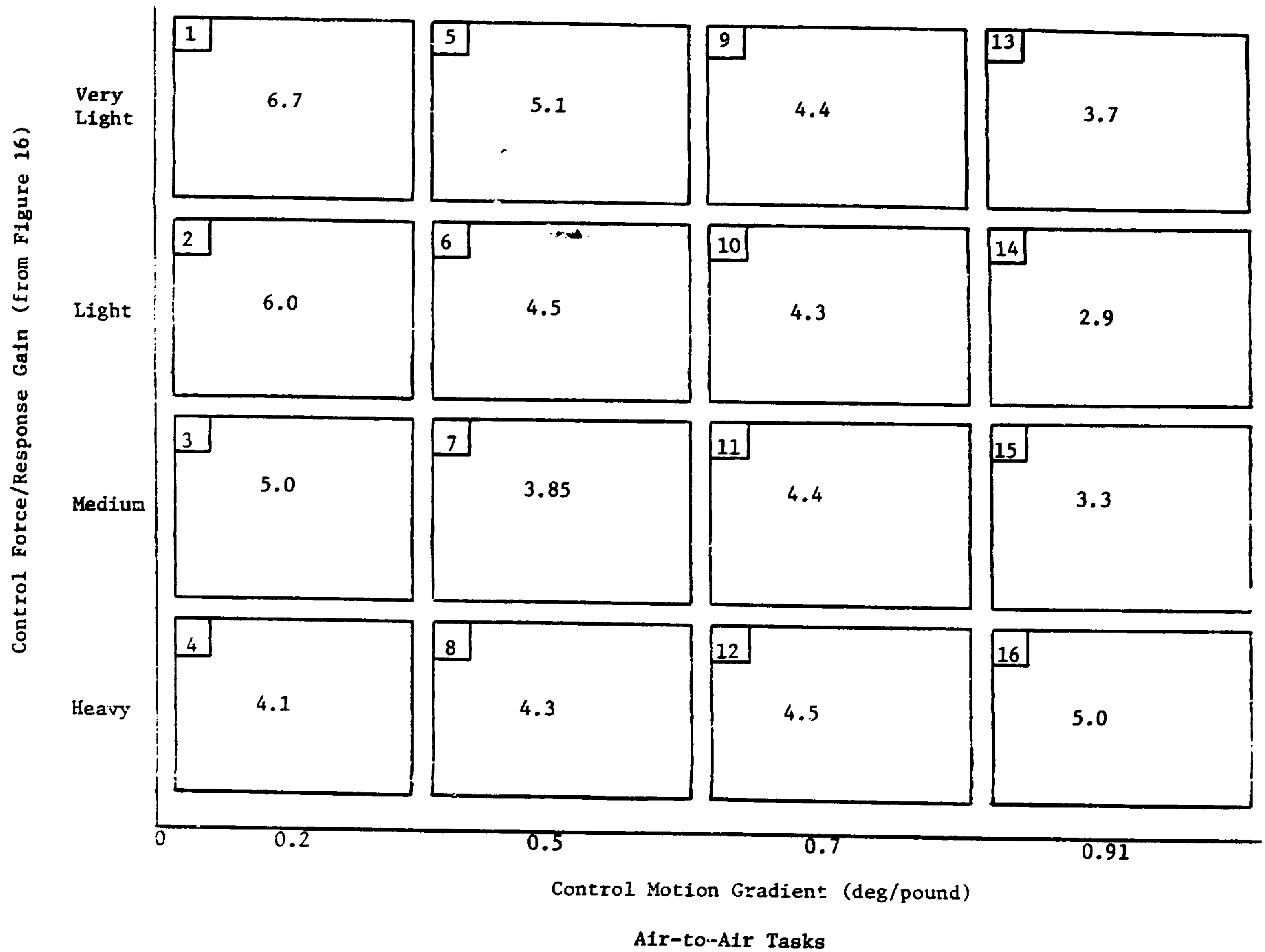


Figure 24 Average Pilot Ratings with Standard Control Harmony

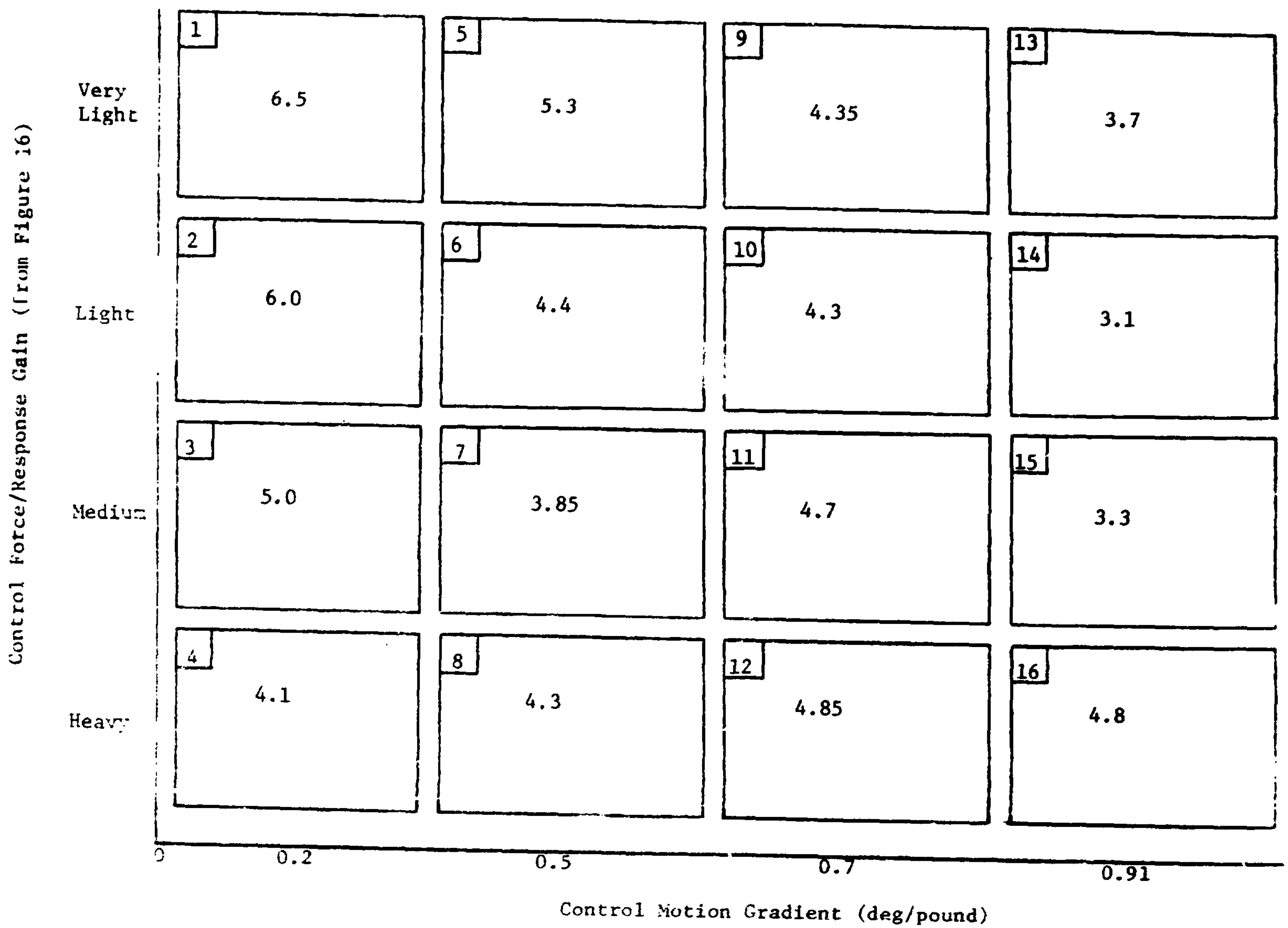
Control Force/Response Gain (from Figure 16)	0.2	0.5	0.7	0.91
Very Light	1 Pilot A - Pilot B - 6 Pilot C - 7	5 Pilot A - 5.5 Pilot B - 6 Pilot C - 4.3	9 Pilot A - 4 Pilot B - 4.5 Pilot C - 4.5	13 Pilot A - 5 Pilot B - 4 Pilot C - 2
Light	2 Pilot A - 5.5 Pilot B - 6.5 Pilot C - 6	6 Pilot A - 4.5 Pilot B - 4.3 Pilot C - 4.6	10 Pilot A - 5 Pilot B - 3.5 Pilot C - 4.5	14 Pilot A - 2.5 Pilot B - 4 Pilot C - 2.9
Medium	3 Pilot A - 5.5 Pilot B - 4.5 Pilot C - 5	7 Pilot A - 4 Pilot B - 4 Pilot C - 3.5	11 Pilot A - 6 Pilot B - 3.5 Pilot C - 4.5	15 Pilot A - 4 Pilot B - 4 Pilot C - 2
Heavy	4 Pilot A - 4 Pilot B - 3 Pilot C - 5.25	8 Pilot A - 4 Pilot B - 4.5 Pilot C - 4.5	12 Pilot A - 5 Pilot B - 5 Pilot C - 4	16 Pilot A - 4 Pilot B - 5 Pilot C - 5.5

0

Control Motion Gradient (deg/pound)

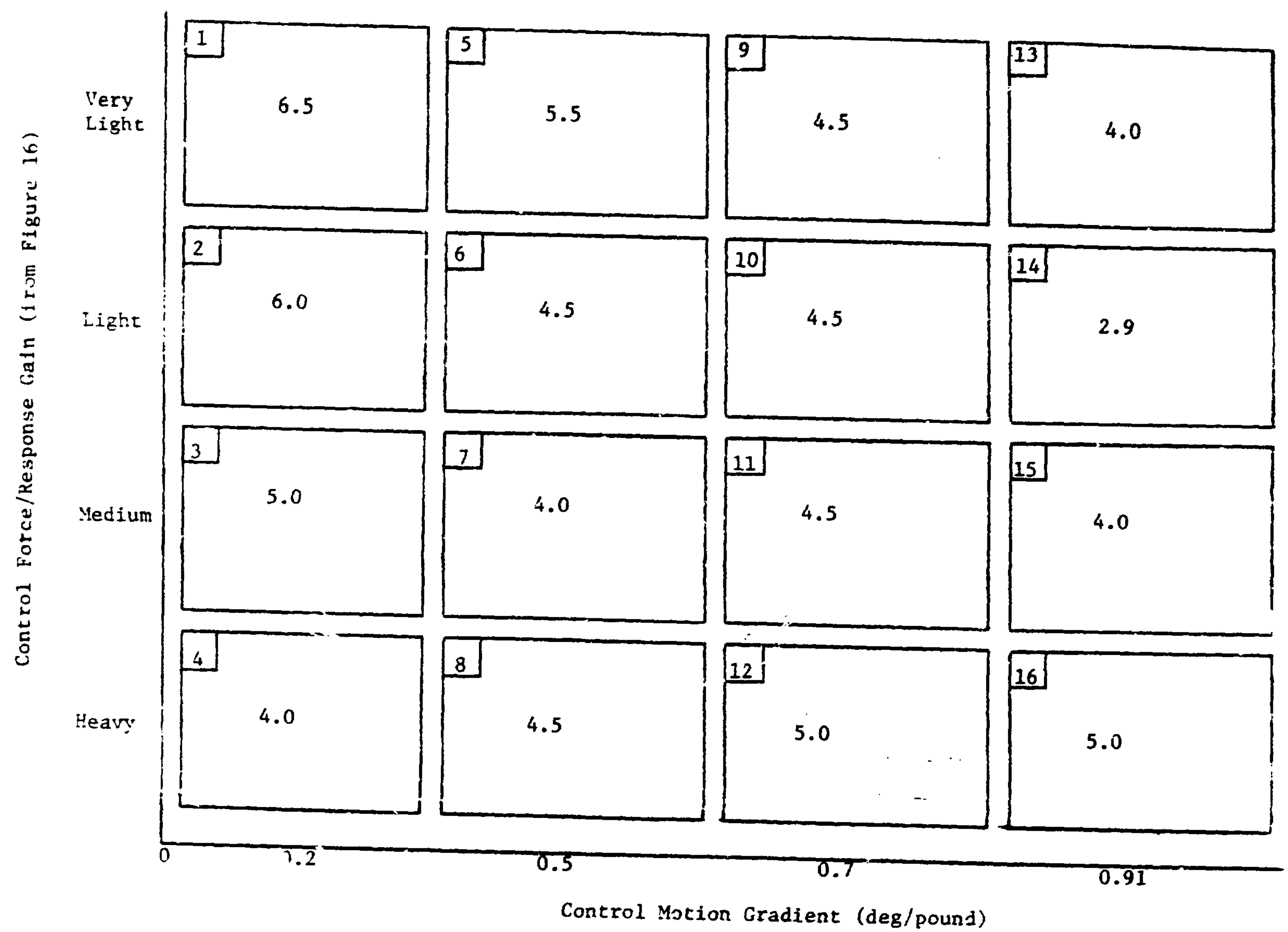
Air-to-Air Tasks

Figure 25 Individual Averages of Pilot Ratings with Standard Control Harmony



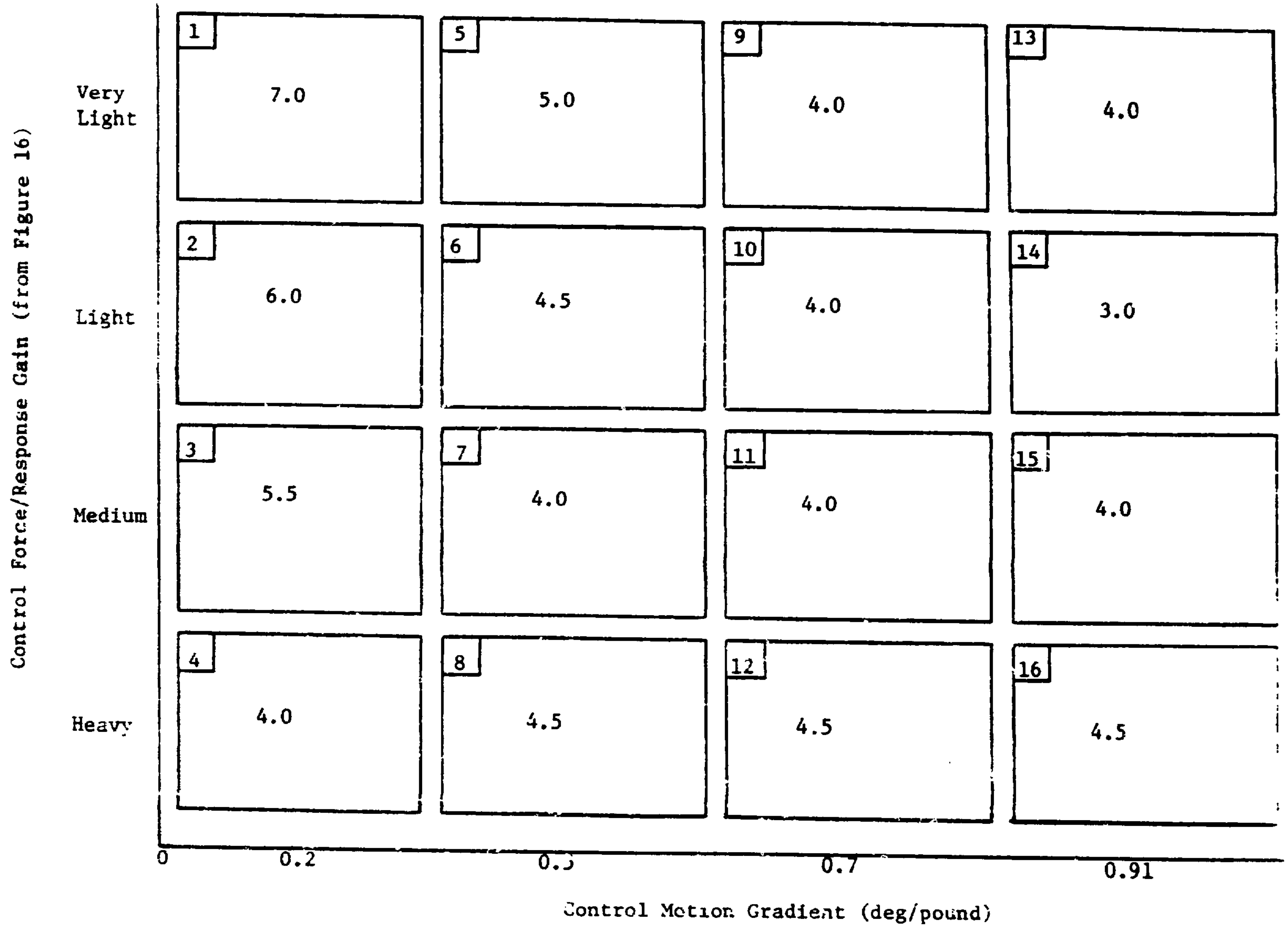
Air-to-Air Tasks

Figure 26 Averages of Individual Pilot Ratings Averages with Standard Control Harmony



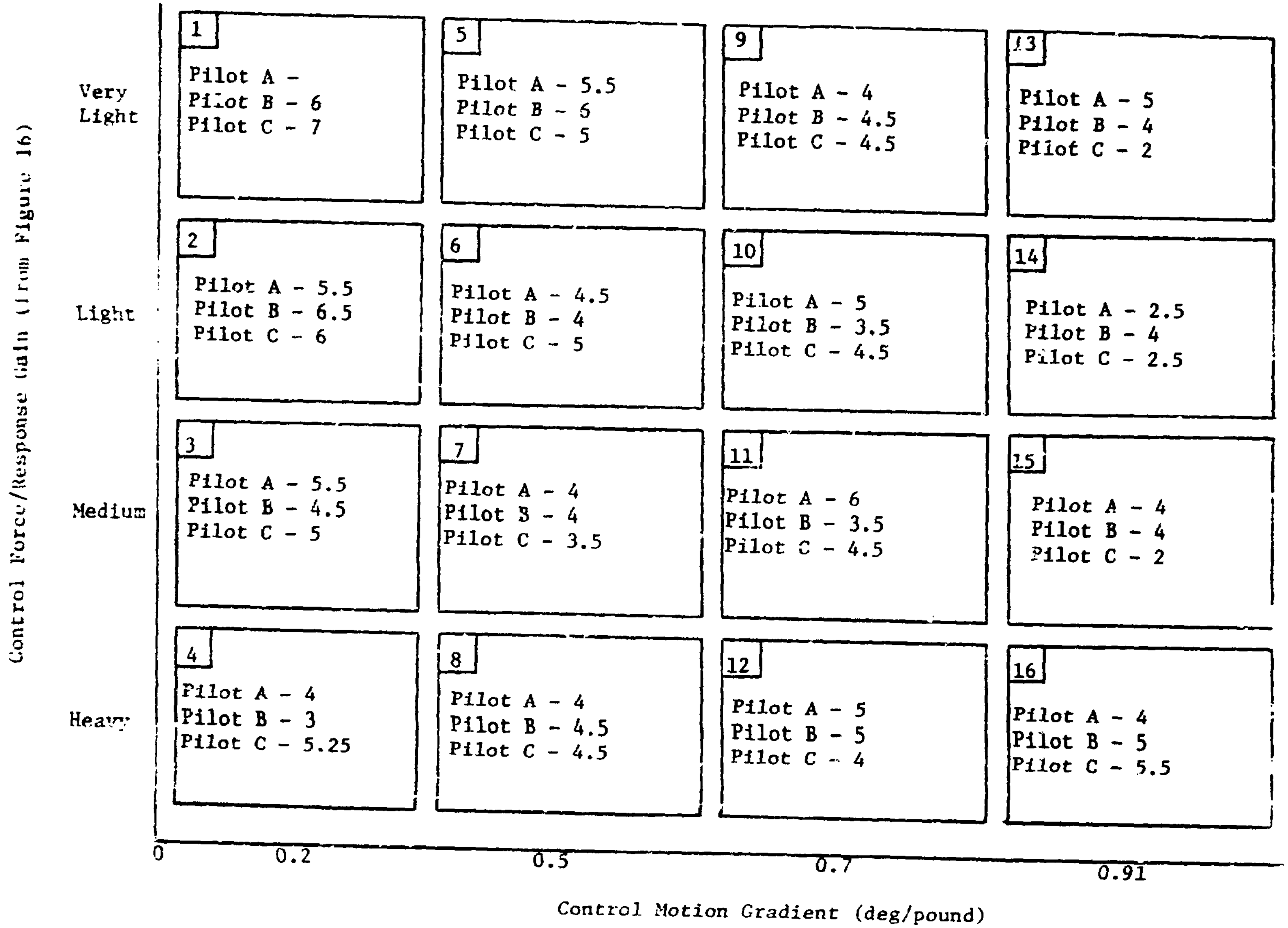
Air-to-Air Tasks

Figure 27 Median of Individual Pilot Averages with Standard Control Harmony



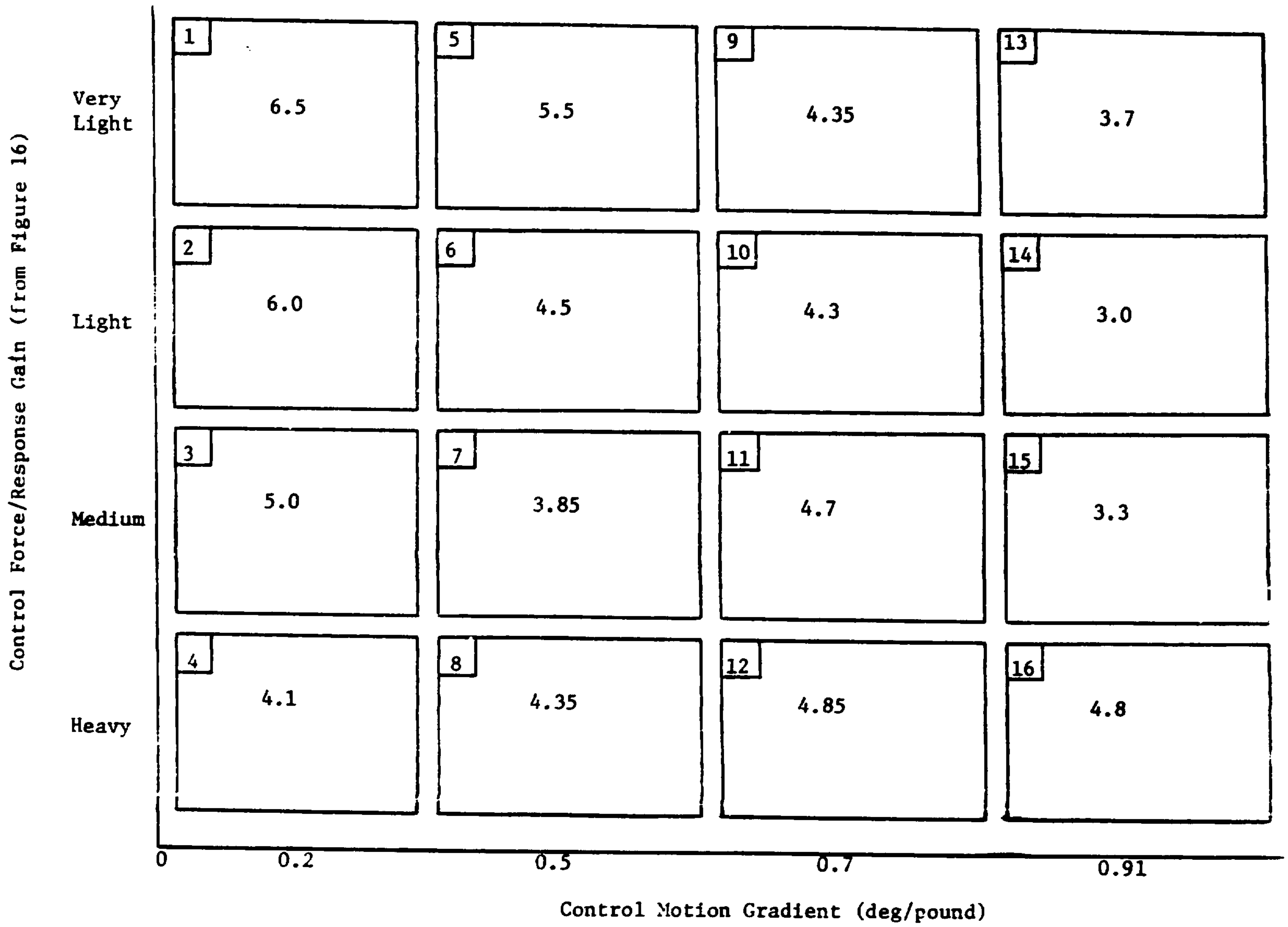
Air-to-Air Tasks

Figure 28 Medians of Pilot Ratings with Standard Control Harmony



Air-to-Air Tasks

Figure 29 **Individual Medians of Pilot Ratings with Standard Control Harmony**



Air-to-Air Tasks

Figure 30 Average of Individual Median Pilot Ratings with Standard Control Harmony

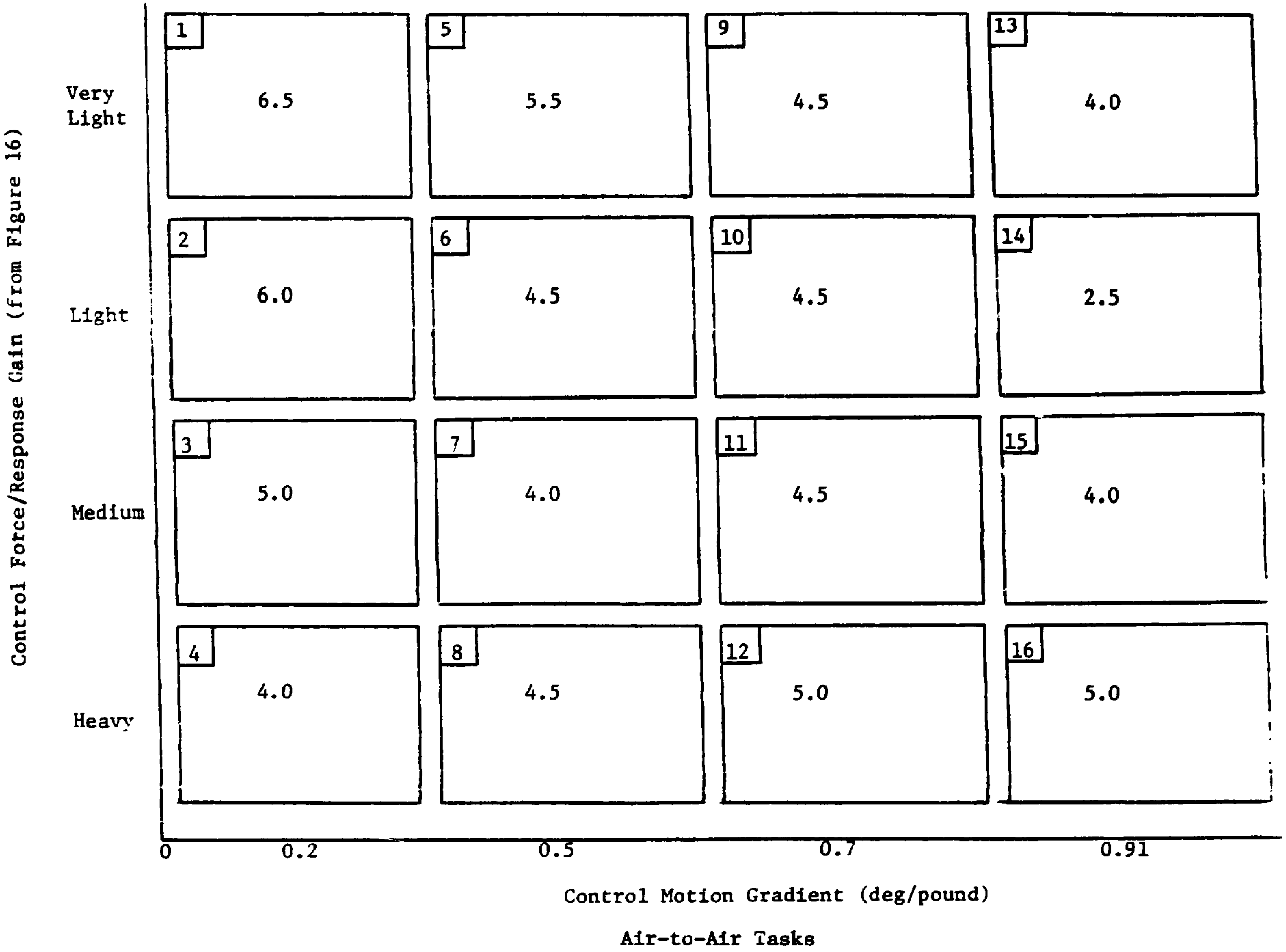


Figure 31 Median of Individual Median Pilot Ratings with Standard Control Harmony

Control Force/Response Gain (from Figure 16)	0.2	0.5	0.7	0.91
Very Light	1: .47	5: 1.12	9: .49	13: 1.25
Light	2: .82	6: .87	10: .94	14: .94
Medium	3: 1.15	7: 1.09	11: 1.02	15: .94
Heavy	4: 1.02	8: .74	12: 1.38	16: 1.22

Control Motion Gradient (deg/pound)

Air-to-Air Tasks

Figure 32 Pilot Rating Standard Deviations with Standard Control Harmony

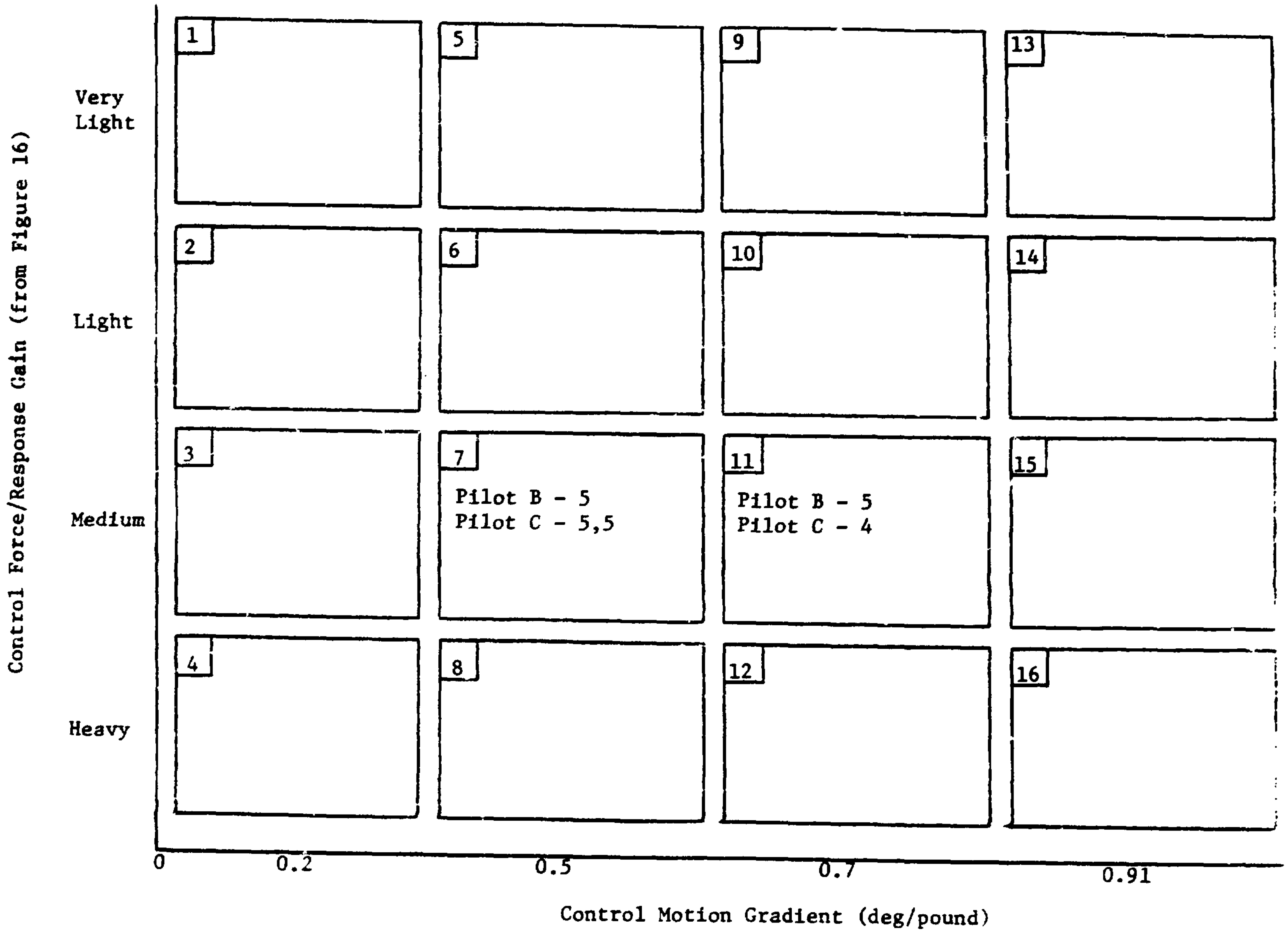


Figure 33 Pilot Ratings for Air-to-Air Tracking with One Pound Breakout Force

for 1/2 pound breakout force. Pilot comments in Figure 34 show an increase in pitch sensitivity with increased breakout force.

Control harmony was investigated for several control configurations where pilot comments indicated a lack of harmony. Lateral forces were increased or decreased one gradient increment for a given longitudinal force gradient. Figures 35 and 37 show that the change in lateral forces resulted in essentially no change in pilot ratings. Pilot comments in Figures 36 and 38 show that increasing or decreasing the lateral force gradient generally resulted in increased sensitivity along the axis with the "lighter feel". Thus the original control force harmony was optimal. However, changes in control motion harmony were not investigated. Additional control harmony testing should be accomplished.

The aircraft lateral-directional characteristics selected for this evaluation were not well suited for the Twisdale air-to-air tracking task. Sharp lateral inputs resulted in annoying low frequency directional oscillations for all control configurations. This deficiency detracted from the pilot's ability to evaluate lateral control effectiveness and control harmony.

A minimum of one flight per pilot was necessary to adapt to the Twisdale task and the aircraft dynamics. Gunsight camera film was useful during this phase for aiding pilots in qualitatively evaluating configurations and exchanging ideas on adequate versus desired aircraft performance.

Gunsight camera films from six randomly selected flights were read and reduced to provide pipper position error. Plots resulting from three control configurations are presented in Figures 39 through 41. The tracking error did not correlate completely with pilot ratings since the amount of pilot compensation was not measured. Hence, these plots were not considered useful for this evaluation.

Evaluation of the air-to-air tracking task was considered primary and a target aircraft was available for each test sortie. This limited the number of air-to-ground and approach and landing tasks that could be accomplished. Only 12 pilot ratings, shown in Figure 42 were obtained for the air-to-ground tracking task. This amount of data was insufficient to present conclusions on the control configurations.

Approach and landing data are presented in Figures 43, 44 and 45. Pilot comments and ratings indicated that approach and landing should be evaluated as two separate tasks. Further, the approach tracking task did not enable the pilots to finely discriminate between control configurations. Though insufficient data were obtained to present conclusions, nearly all control configurations seemed to accomplish the approach tracking task equally well. The landing task enabled pilots to discriminate more easily between control configurations. Additional testing should be accomplished to optimize the control configurations for the landing task.

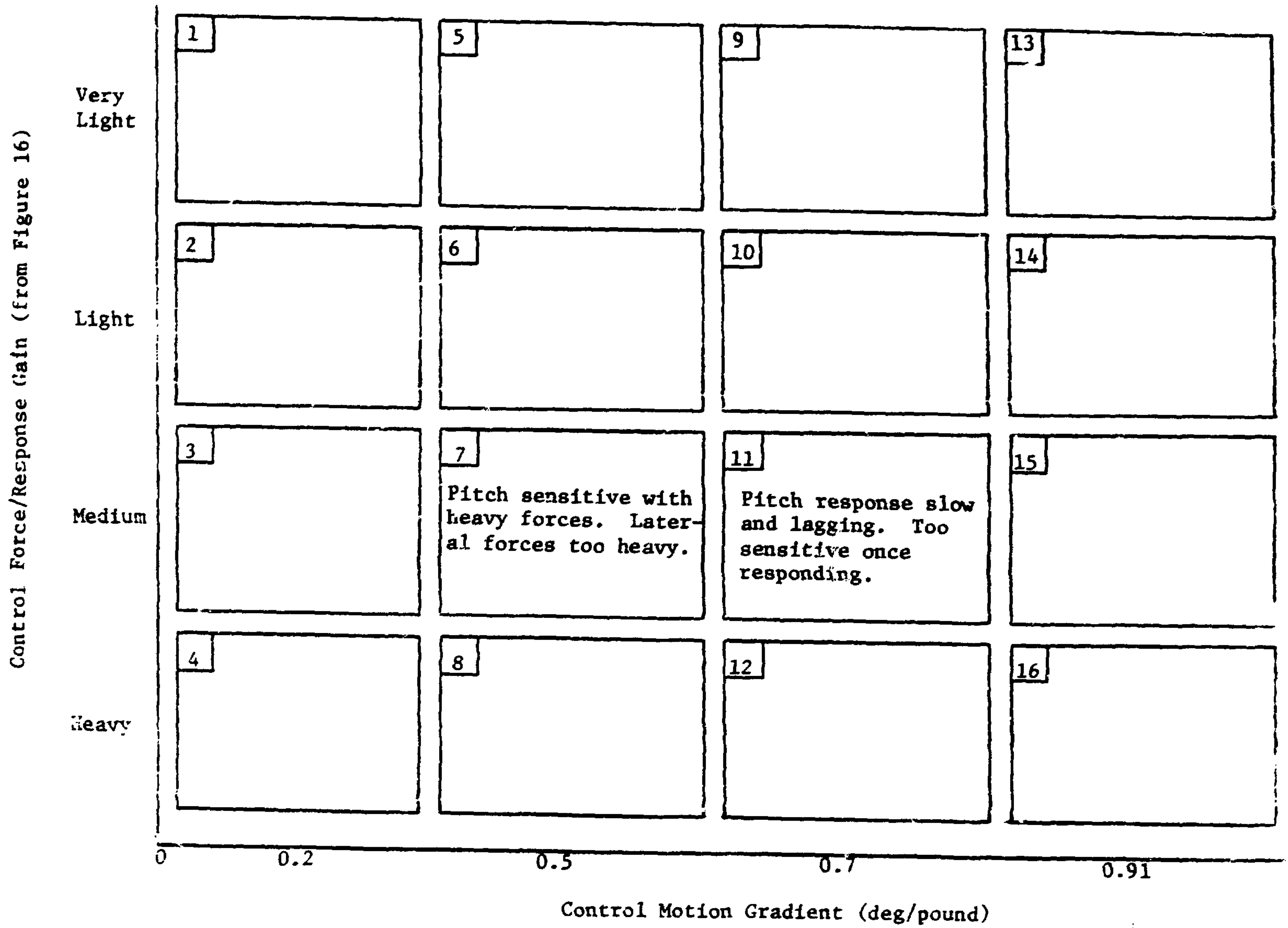


Figure 34 Pilot Comments for Air-to-Air Tracking with One Pound Breakout Force

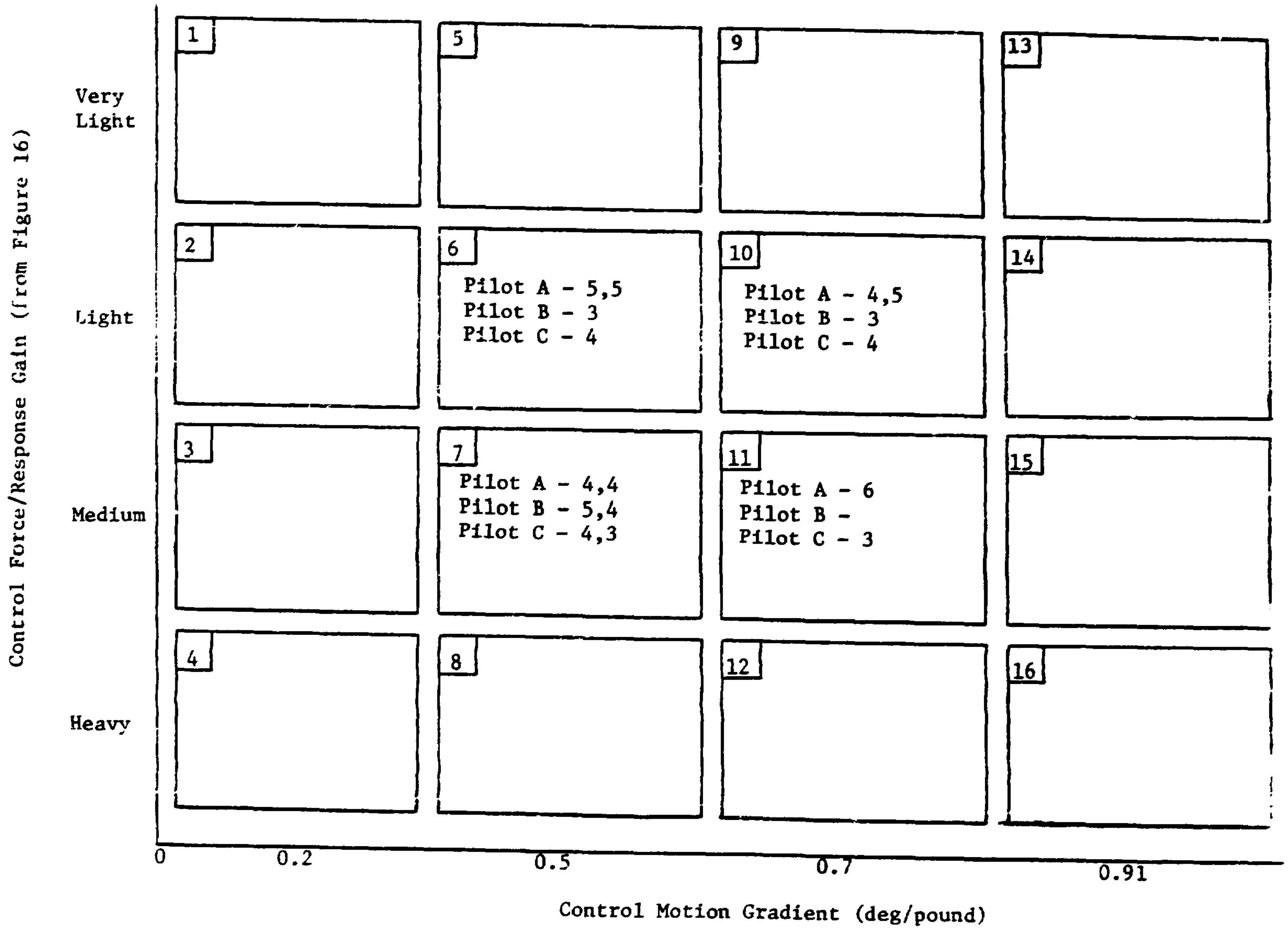


Figure 35 Pilot Ratings for Air-to-Air Tasks with Lighter Lateral Force Gradients

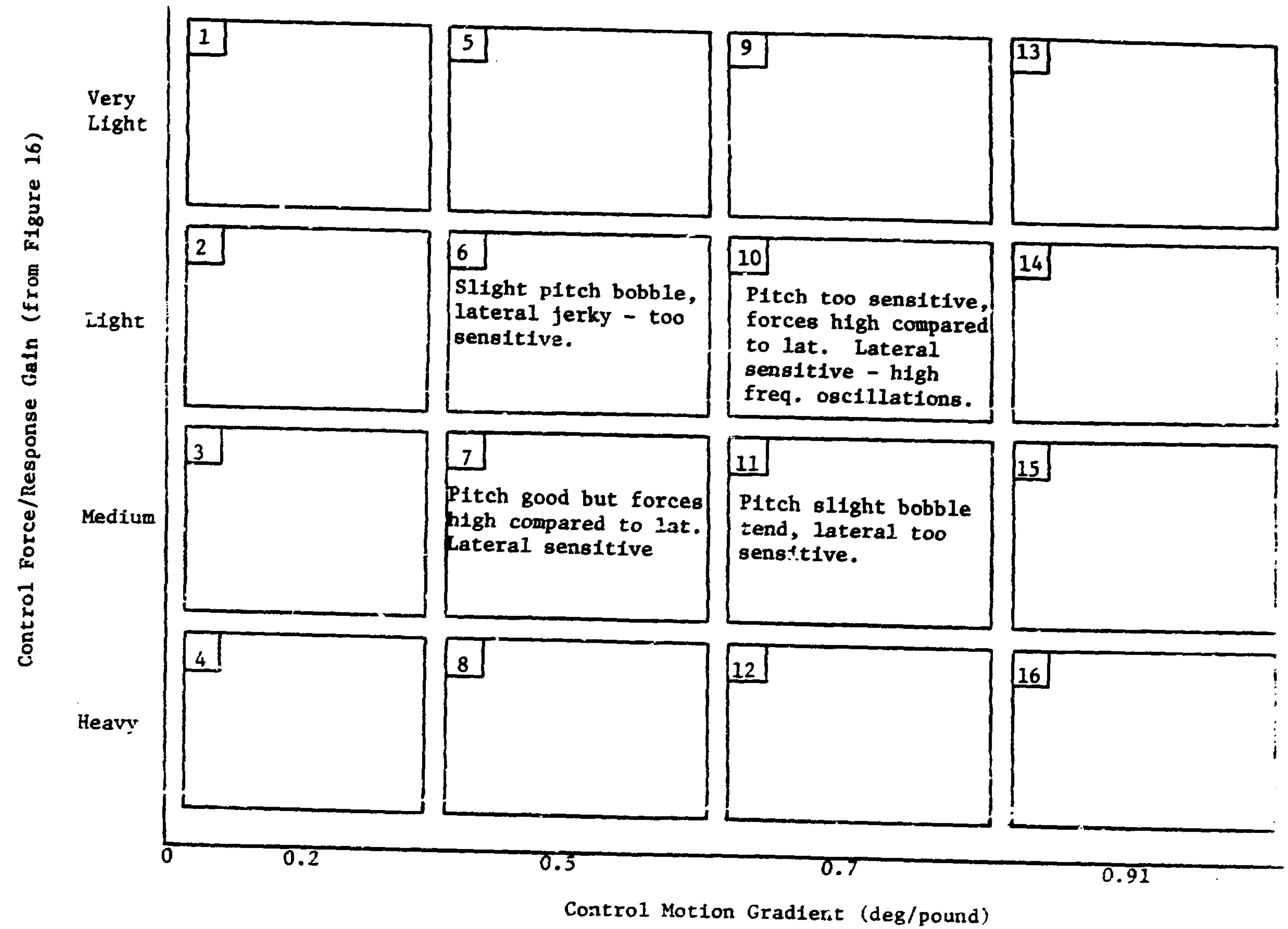


Figure 36 Pilot Comments for Air-to-Air Tasks with Lighter Lateral Force Gradients

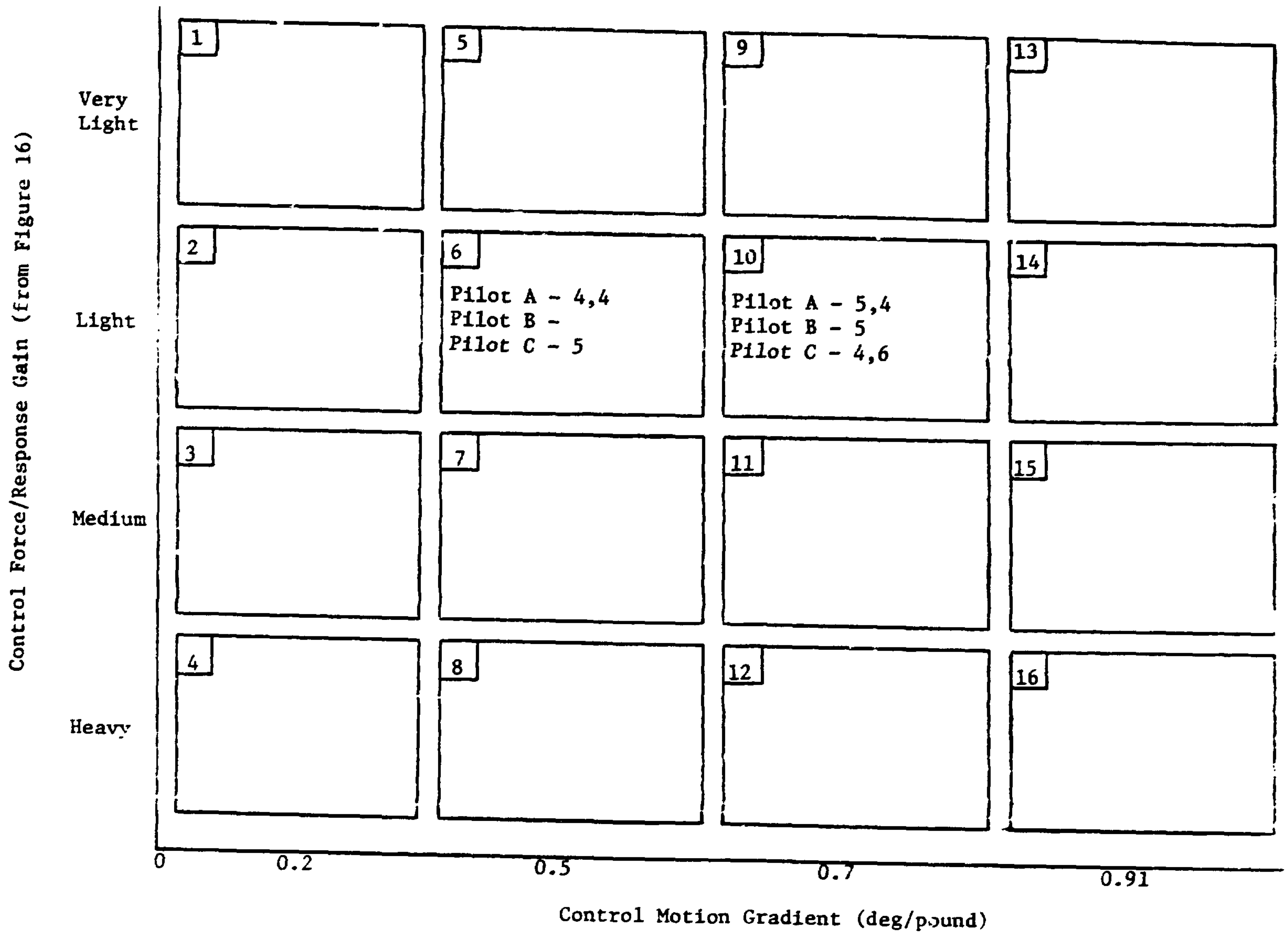


Figure 37 Pilot Ratings for Air-to-Air Tasks with Heavier Lateral Force Gradients

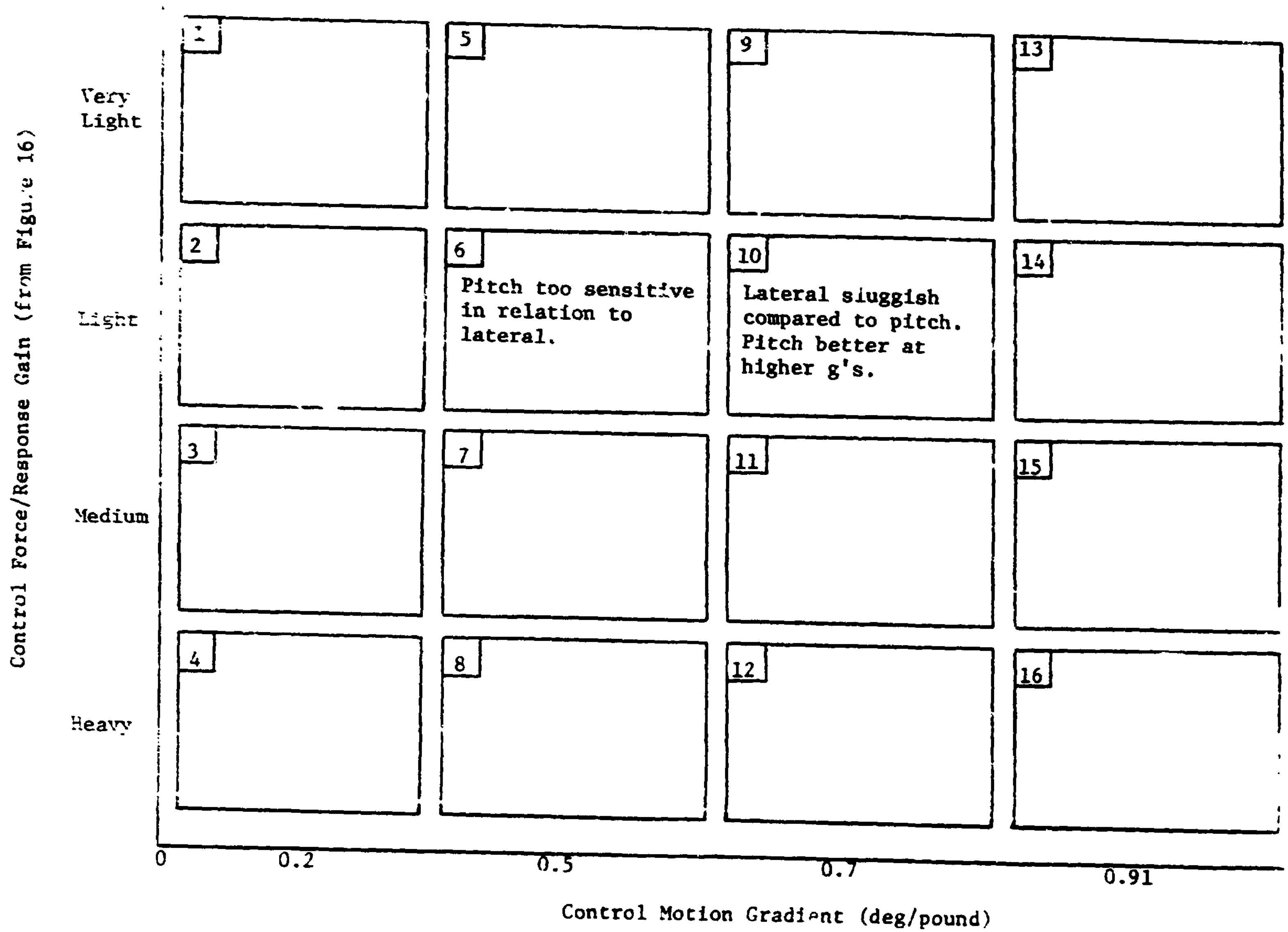


Figure 38 Pilot Comments for Air-to-Air Tasks with Heavier Lateral Force Gradients

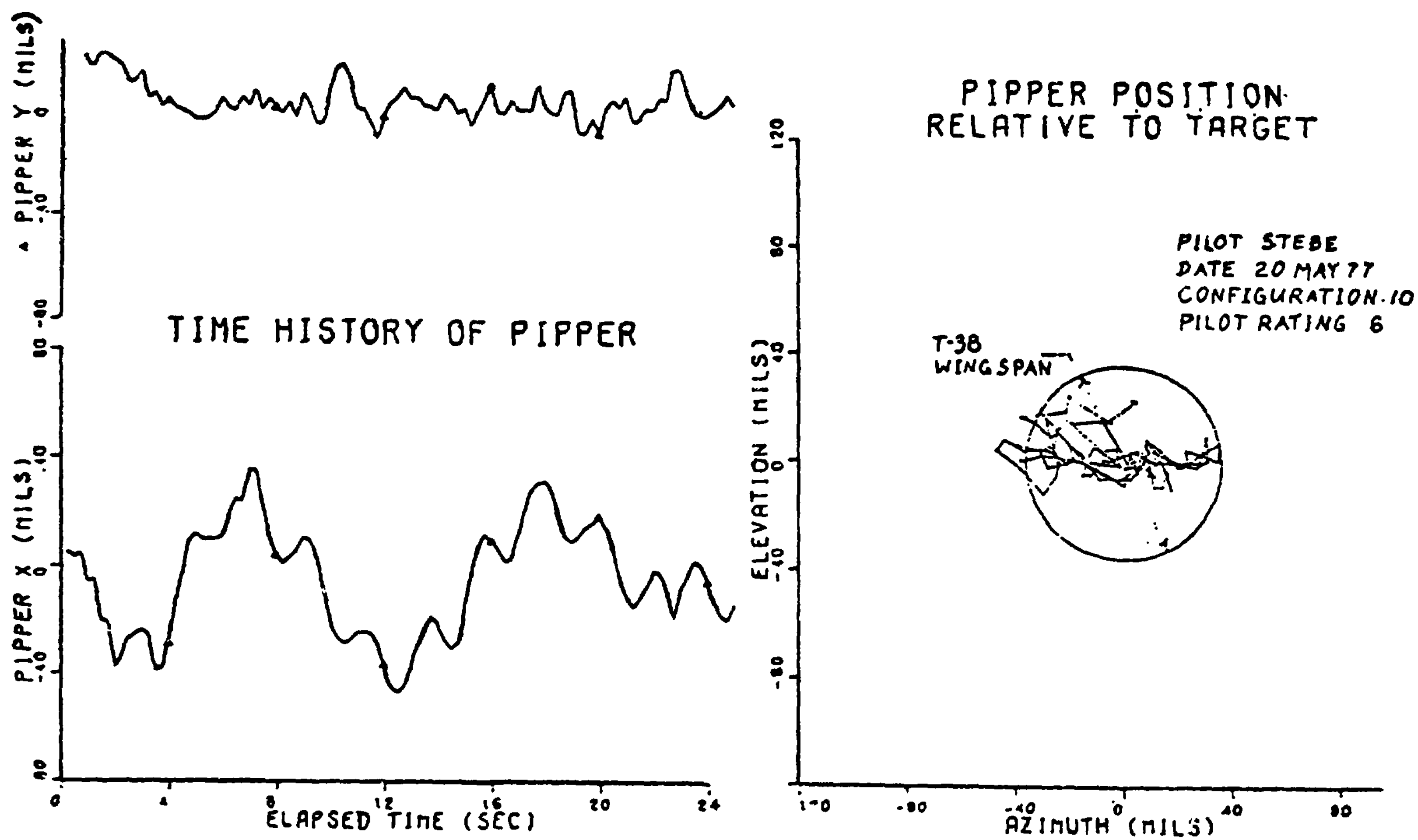


FIGURE 39 Plots of Pipper Motion (Configuration 10)

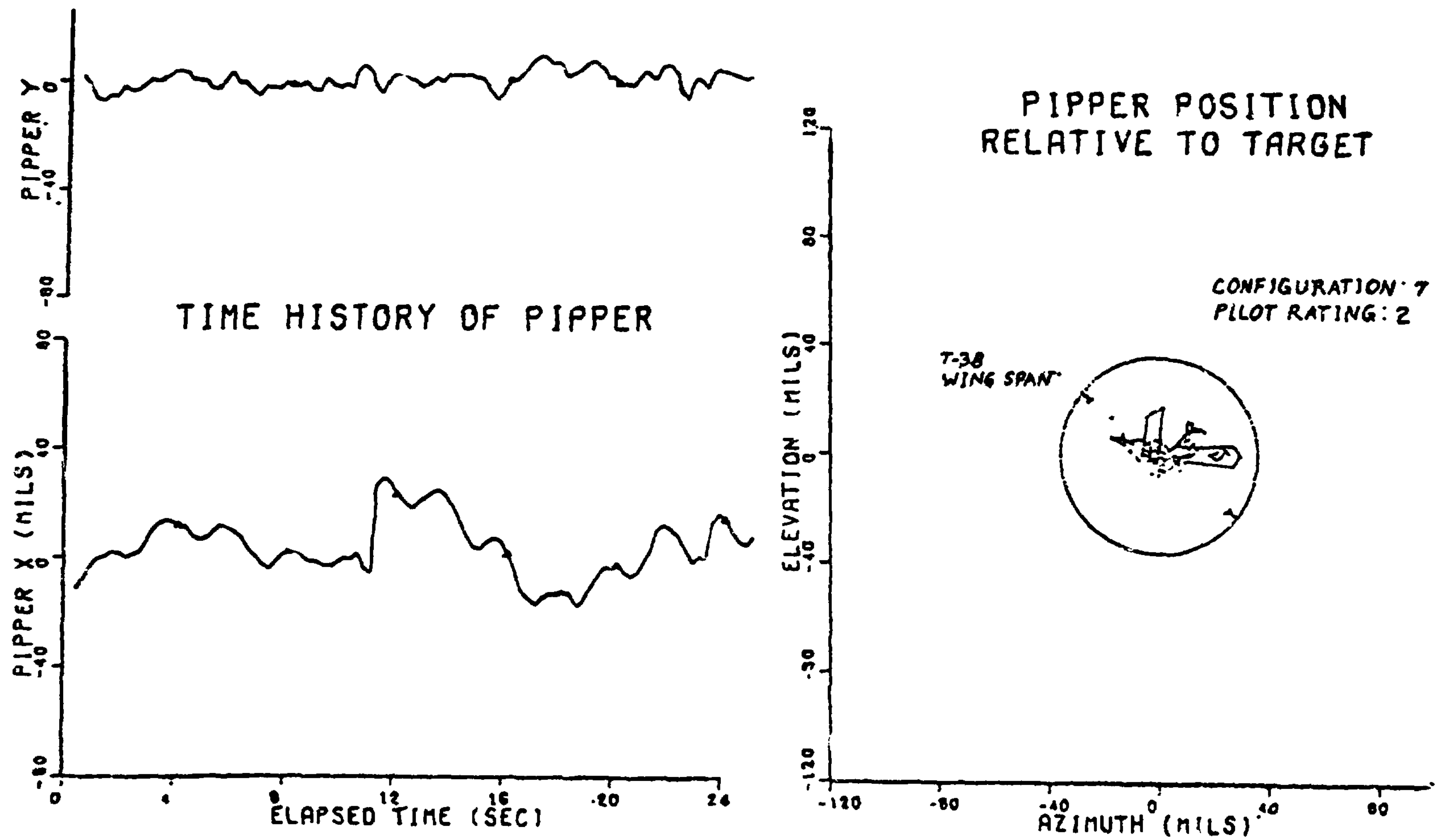


FIGURE 40 Plots of Pipper Motion (Configuration 7)

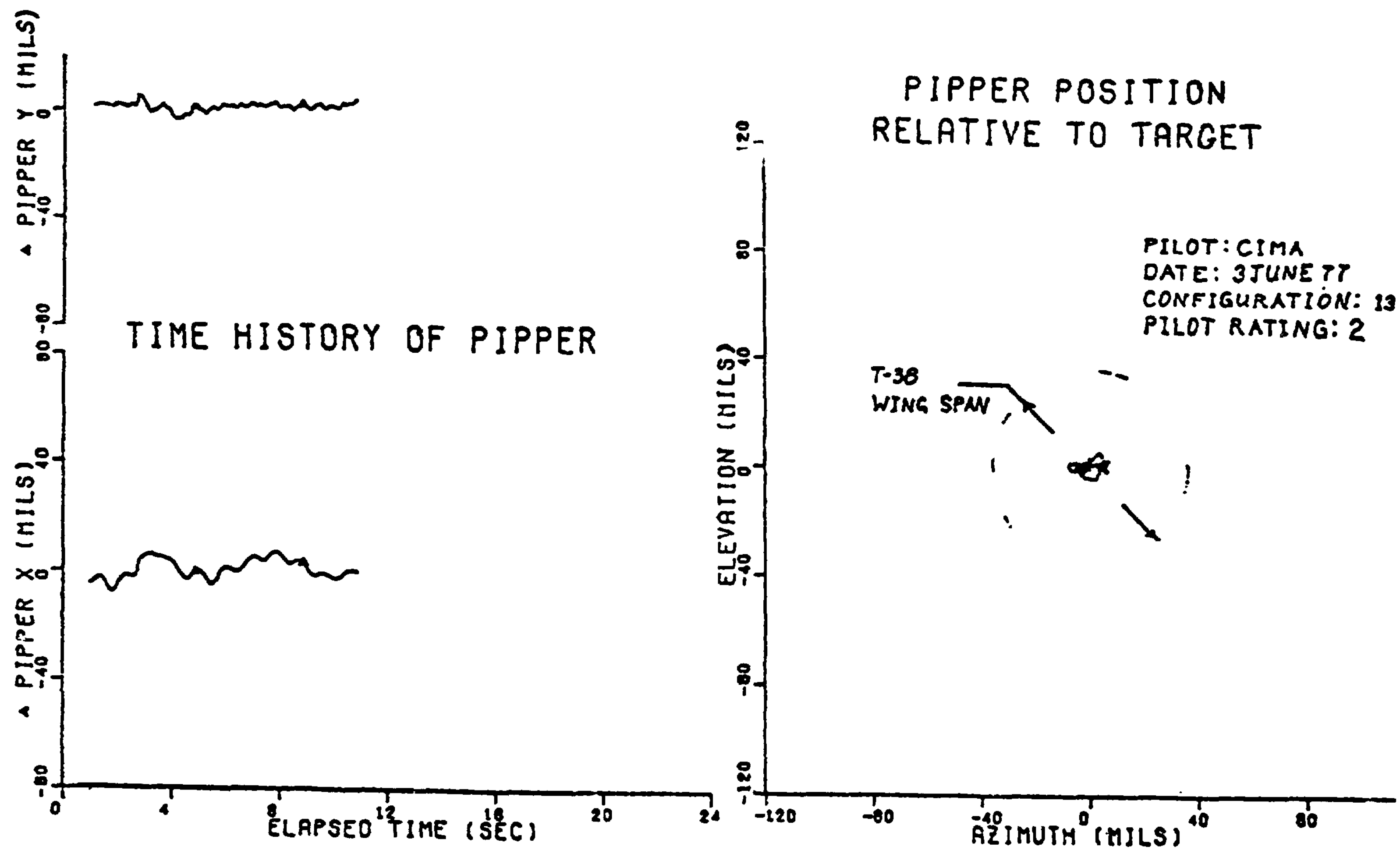


FIGURE 41 Plots of Pipper Motion (Configuration 13)

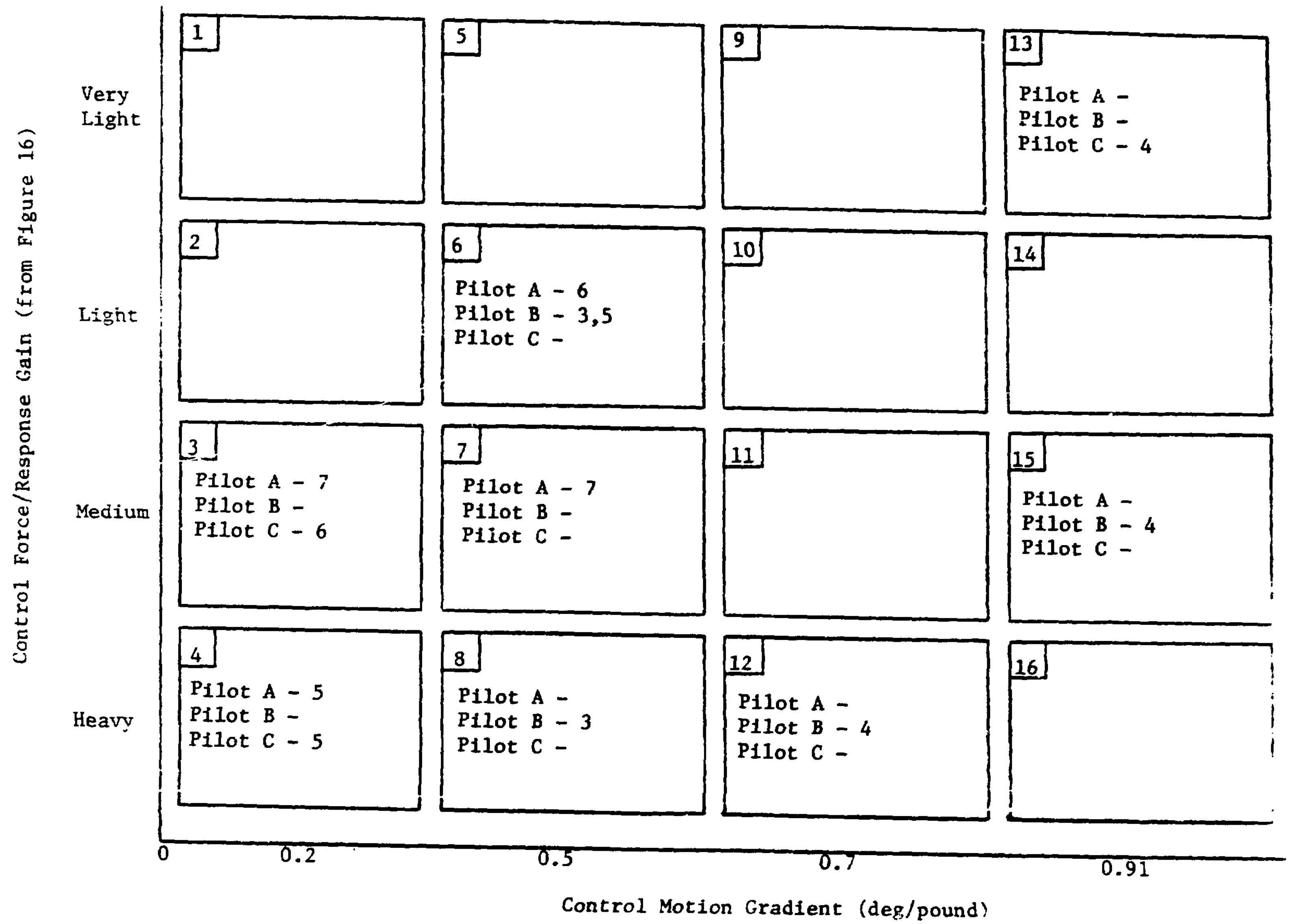


Figure 42 Pilot Ratings for Air-to-Ground Tracking Tasks with Standard Control Harmony

Control Force/Response Gain (from Figure 17)	0.2	0.5	0.7	0.91
Light	17 Pilot A - Pilot B - 5 Pilot C - 4	19 Pilot A - 6 Pilot B - 4 Pilot C - 5,3,3	21	23
Medium	18 Pilot A - 5.3 Pilot B - 3 Pilot C - 5	20 Pilot A - Pilot B - Pilot C - 3	22	24 Pilot A - 6 Pilot B - 5 Pilot C - 7

0 0.2 0.5 0.7 0.91

Control Motion Gradient (deg/pound)

Figure 43. Pilot Ratings for Approach Task

Control Force/Response Gain (from Figure 17)	0.2	0.5	0.7	0.91
Light	17 Pilot A - Pilot B - 5 Pilot C - 2	19 Pilot A - 3,6 Pilot B - 3,4 Pilot C - 4,5,5	21	23
Medium	18 Pilot A - 3,4 Pilot B - 3 Pilot C - 5	20 Pilot A - Pilot B - Pilot C - 3	22	24 Pilot A - 6 Pilot B - 5 Pilot C - 6

0 0.2 0.5 0.7 0.91

Control Motion Gradient (deg/pound)

Figure 44. Pilot Ratings for Landing Tasks

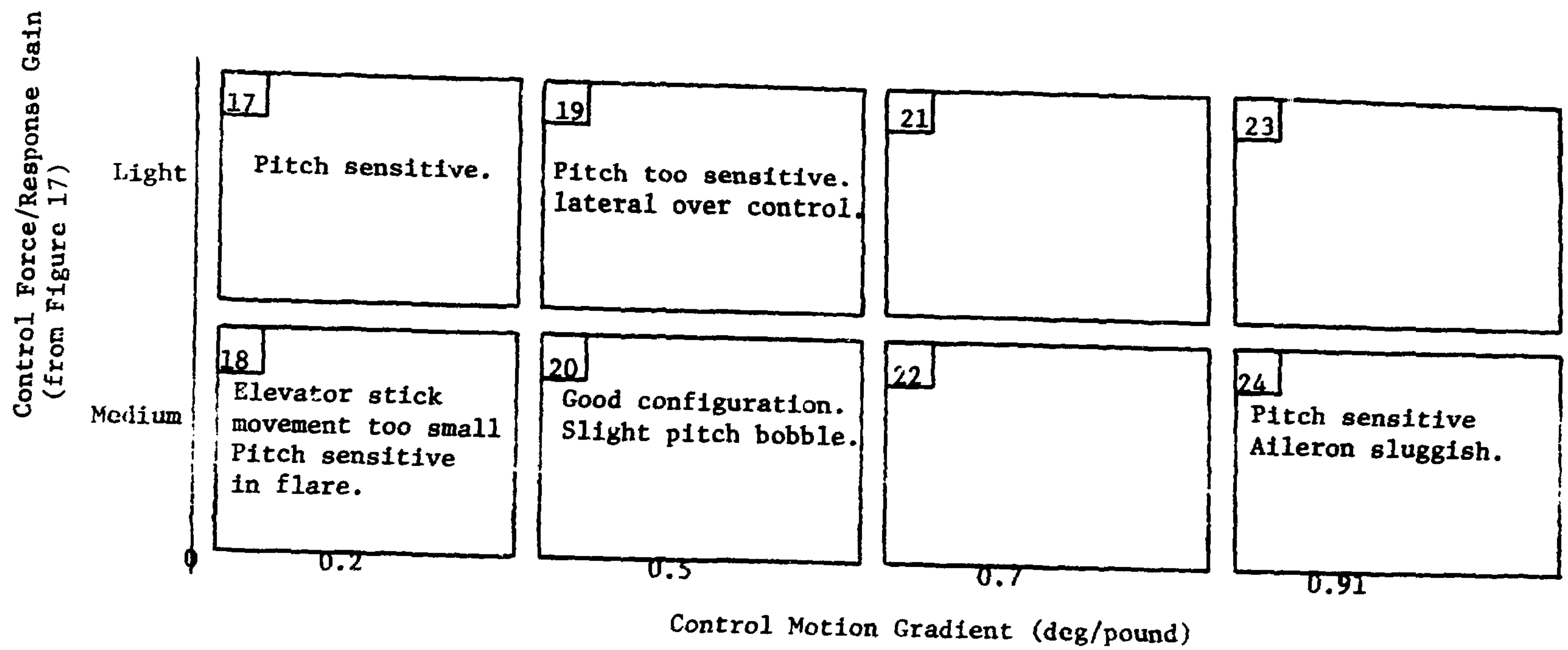


Figure 45. Typical Pilot Comments for the Approach and Landing Tasks

The pilot ratings and comments presented in this report were obtained using the specific tasks described in the Test Methods section. Other Category A and C tasks, such as gross maneuvering or formation flying, could result in different ratings and comments for the same control configurations. Additional testing should be conducted to determine the applicability of this test data to Category A and C tasks of broader scope.

CONCLUSIONS AND RECOMMENDATIONS

The effect of sidestick longitudinal and lateral force and deflection characteristics upon the pilot rating of aircraft handling qualities in Flight Phase Categories A and C was investigated. For the air-to-air task, pilots preferred large control stick motion with light control force gradients. Aircraft lateral-directional characteristics detracted from the pilot's ability to evaluate lateral control effectiveness and control harmony. Increasing the breakout force from 1/2 to 1 pound increased pitch sensitivity. The approach tracking task did not enable the pilots to finely discriminate between control configurations.

Pilot ratings for the air-to-air phase correlated well between pilots and exhibited a standard deviation of approximately one for each control configuration.

1. These data should be used in specifying requirements and design criteria for Class IV aircraft with sidestick controllers.

Configurations with the best ratings involved large stick motion and were on the edge of the test matrix; thus, the extent of this area was not determined.

2. Additional testing should be accomplished to completely define the area of best ratings.

The control harmony investigation was incomplete in that control motion harmony was not evaluated.

3. Additional control harmony testing should be accomplished.

Insufficient data were obtained for Category C tracking tasks to present conclusions.

4. Additional testing should be accomplished to optimize the control configuration for the landing task.

Other Category A and C tasks, such as gross maneuvering or formation flying, could result in different ratings and comments for the same control configurations.

5. Additional testing should be conducted to determine the applicability of this test data to Category A and C tasks of broader scope.

APPENDIX C

TECHNICAL RESULTS AND DISCUSSION FROM USAF TEST PILOT SCHOOL LETTER REPORT - 9 December 1977 "Limited Flight Evaluation of the Effect of Sidestick Force/Deflection Characteristics on Aircraft Handling Qualities" by Vernon P. Saxon, Captain, USAF; Edward L. Daniel, Captain, USAF; Cecil D. Haas, Captain, USAF; David G. LaBarge, Captain, USAF; Jerry D. Pfleeger, Captain, USAF; Vernon S. Ritchey, Captain, USAF and Guy C. Thiel, Captain, USAF.

ABSTRACT

A limited investigation was conducted to determine the impact of varying sidestick force and deflection gradients on pilot ratings of aircraft handling qualities. The test aircraft, AFFDL's variable stability NT-33A, was configured with the aircraft dynamic characteristics of a high performance fighter similar to an F-16. The region of sidestick force and deflection characteristics which produced acceptable handling qualities was defined for the tasks of formation, air-to-air fine tracking, gross acquisition, and landings. A near optimum control configuration was identified for the aircraft and control system dynamics tested. Although initially planned, quantitative tracking data and control harmony investigations were not accomplished due to limited area sorties. The data presented are in the form of pilot commentary supplemented by Cooper-Harper ratings. These data can be used to further expand the data base on sidestick control configurations generated in previous evaluations of this type. Data, target support, practice and calibration flights totalling 48 sorties and 65 flying hours were flown at the Air Force Flight Test Center, Edwards AFB, California from 26 October to 25 November 1977.

TEST OBJECTIVES

The overall test objectives were to investigate the influence of sidestick response/force gains and deflection/force gradients on pilot evaluation of aircraft handling qualities in formation flying, gross acquisition, fine tracking and landing tasks.

The specific test objectives were:

1. To examine the impact of varying sidestick characteristics upon pilot evaluations of aircraft handling qualities. Sidestick characteristics were changed by varying the normal acceleration per unit longitudinal sidestick force (N_z/F_{es}) and longitudinal sidestick deflection per unit force (δ_{es}/F_{es}) along with roll rate per unit lateral force (P/F_{as}) and lateral sidestick deflection per unit lateral force (δ_{as}/F_{as}) for selected Category A and C phase flight tasks.

2. Quantitative verification of task performance and correlation of pilot performance with pilot ratings was to be obtained through supportive data of tracking accuracy for air-to-air tracking tasks.

The secondary test objective was to obtain pilot evaluation of aircraft handling qualities with variations in control harmony.

TEST CONFIGURATIONS

The NT-33 variable stability control system was configured to simulate the airframe dynamics of a "good" airplane as shown in Table V. During the evaluation, the elevator and aileron control force gradients (G's/Lb and Roll Rate/Lb) and sidestick deflection gradients (Degrees/Lb) were varied to obtain the various test configurations as shown in Figure 46. The breakout force was 0.5 Lb and the force command was conditioned by a pre-filter for both axes. The pre-filters were simple first order lags with break frequencies at 8 radian/sec for air-to-air tasks, and 4 radian/sec for landing tasks. To maintain constant roll dynamics, it was necessary to reduce roll damping and aileron control gain as fuel was depleted. Control system potentiometer settings were computed for 600, 500, 400 and 300 gallons of fuel remaining, and the settings for the nearest fuel quantity were used.

Prior to the first data flight, a calibration sortie was flown to determine potentiometer settings required to obtain the desired force and deflection gradients. At the end of the evaluation, another calibration flight was flown to verify the gradients. Slight changes in the gradients were observed between the two calibration flights; however, these changes should not affect the results of the tests. The results of both calibration flights are shown in Tables VI and VII.

TABLE V

AIRFRAME DYNAMICS

	Air-to-air[1]	Landing[2]	Units
n_z/α	20	3.7	
Short period frequency	6	3.3	Rad/Sec
Short period damping ratio	0.6	0.2	
Dutch roll frequency	2.3	1.7	Rad/Sec
Dutch roll damping ratio	0.16	0.07	
ϕ/β	0.4	3	
Roll mode time constant	0.35	0.50	Sec

1. 300 KIAS, 15,000 ft MSL, cruise configurations
2. 130 KIAS, 7,000 ft MSL, flaps 30°, gear down

	Deflection Gradient (Deg/lb)							
	0.18	0.38	0.57	0.73	0.96	1.10	1.20	Elevator
Force Gradient	0.12	0.42	0.77	1.09	1.35	1.65	1.80	Aileron
Extremely light	1	7	13	19	25	31	37	
Very light	2	8	14	20	26	32	38	
Light	3	9	15	21	27	33	39	
Medium	4	10	16	22	28	34	40	
Heavy	5	11	17	23	29	35	41	
Very heavy	6	12	18	24	30	36	42	

FIGURE 46. Test Configurations

TABLE VI

CONTROL FORCE GRADIENTS

Pitch Axis (G's/lb)[1]				
Descriptor	Pre Test Data		Post Test Data	
	Air-To-Air	Landing	Air-To-Air	Landing
Extremely light	0.50	0.082	-	-
Very light	0.33	0.053	0.29	0.058
Light	0.25	0.039	0.21	0.038
Medium	0.16	0.024	0.14	0.026
Heavy	0.12	0.016	0.10	0.019
Very heavy	0.09	0.011	0.06	0.012
Roll Axis (Deg/Sec/lb)[2]				
Descriptor	Pre Test Data		Post Test Data	
	Air-To-Air	Landing	Air-To-Air	Landing
Extremely light	23	14.8	-	-
Very light	15	9.6	15	10.3
Light	11	7.2	11	7.7
Medium	7	4.4	7	4.5
Heavy	4.6	2.9	4.4	3.1
Very heavy	3.2	2.0	2.7	1.6

1. Half pound breakout; above 4 lb, gradient doubles
2. Half pound breakout; above 3 lb, gradient doubles

TABLE VII

CONTROL DEFLECTION GRADIENTS

(Deg/Lb)

Pre Test Data		Post Test Data	
Pitch Axis	Roll Axis	Pitch Axis	Roll Axis
0.10	0.15	0.18	0.12
0.30	0.45	0.38	0.42
0.50	0.75	0.57	0.77
0.70	1.05	0.73	1.09
0.90	1.35	0.96	1.35
1.10	1.65	-	-
1.20	1.80	-	-

Since the data from the last calibration flight is probably more accurate, that data was used throughout the remainder of the report.

TEST METHODS AND CONDITIONS

Pre-test and post test calibration sorties were planned to determine the sidestick force and deflection gradients for the test conditions. The data from the pre-test calibration sortie was used to determine the variable stability system gain (potentiometer) settings to obtain the desired gradients. The oscillograph was used to record the pilot force inputs, sidestick deflections, and aircraft response. The pre-test calibration was repeated twice because of oscillograph feed system failure during the first two attempts. The post test calibration sorties was used to determine the NT-33A apparent open loop dynamics and to recheck the force and deflection gradients at the end of the program.

The tests were conducted using the configurations shown in Figure 47. Configurations 27, 16 and 11 were found to be likely candidates for an optimal configuration by USAF TPS Class 76B (Appendix B). Therefore, the nine configurations shown as initial were examined during the first eight data sorties to identify regions that justify further testing. The pilot ratings from the first eight sorties showed no clear preference for any configuration and large variability between pilots. Therefore, for the second eight sorties, configurations outside the initial set of points were used for most of the evaluations. Throughout the first sixteen data sorties, configurations were chosen in a pseudo-random fashion where engineering judgement was used to avoid an excessive number of evaluations of any configuration (while neglecting others) or evaluating nearly identical configurations on the same sortie. At the completion of the fourteenth data sortie, the trends which will be discussed under Analysis of Configurations were detected by the project engineers. Therefore, the last two data sorties were used to verify the sensitivity conclusions by traversing the test envelope in the direction of maximum sensitivity change. Also, a near optimal configuration was chosen based on pilot comments and ratings. This near optimal configuration was evaluated on the last data sortie. Throughout the test, evaluation pilots were never told which configurations they would evaluate.

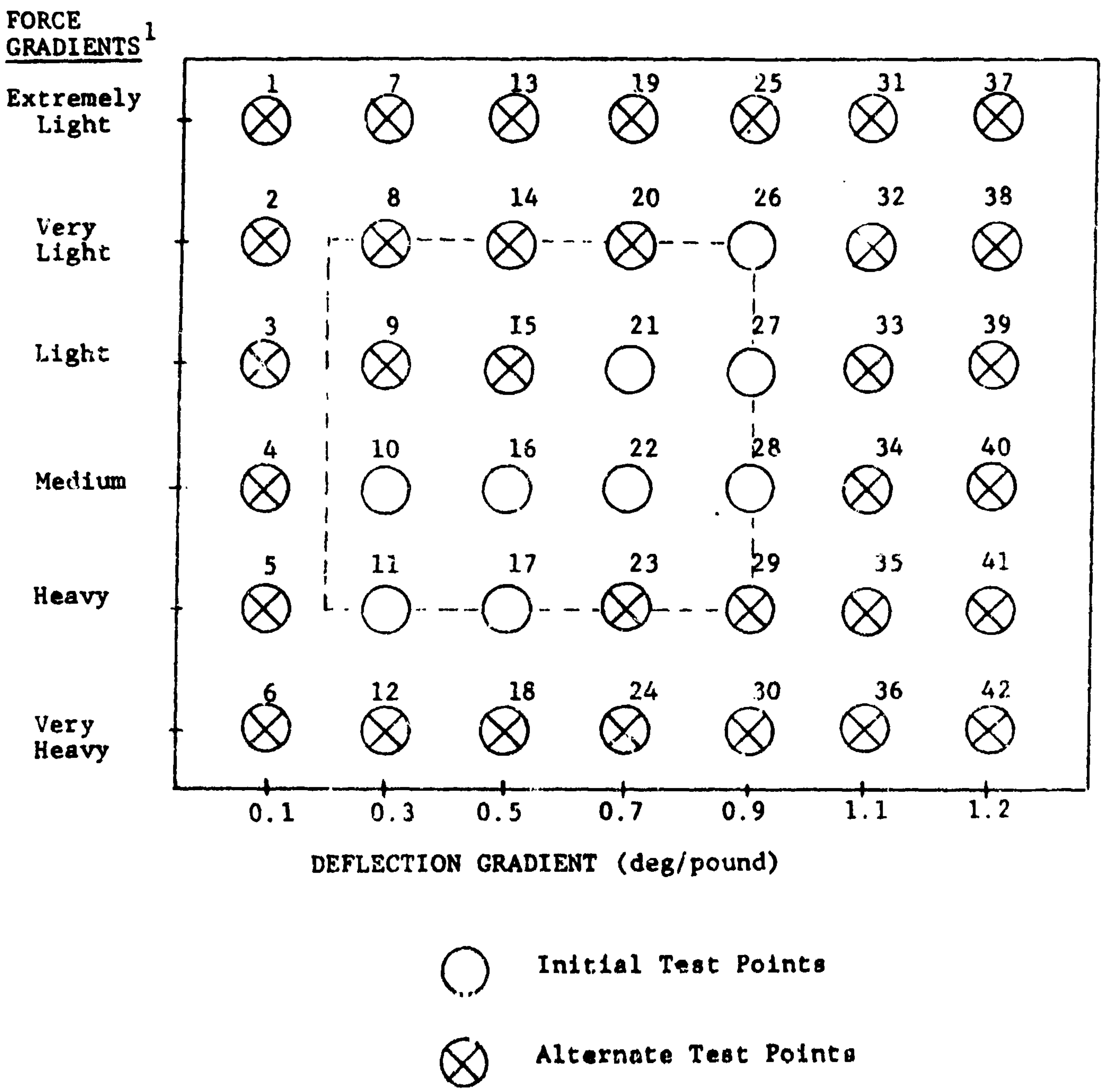
Mission Description.

Each mission consisted of the following phases:

a. Pre-mission briefing

b. Takeoff and join-up

c. Tracking tasks, to include:



NOTE: Lateral deflection is approximately 1.5 times the longitudinal deflection gradient.

[1]See Test Configuration section for definitions of force and deflection gradients.

FIGURE 47. CONTROL CONFIGURATIONS

1. Formation work

2. Wind-up turn

3. 3-g turns with rapid reversals

4. 2½-g cine-track maneuver

d. Approach and landing task

e. Debriefing

Pre-Mission Briefing. Mission briefings were conducted by the test mission aircrews and the project engineer monitoring that flight. The target aircrew consisted of a project pilot and project engineer.

Takeoff and Join-Up. The T-38 target aircraft made a military power takeoff 20 seconds after the NT-33 started his takeoff roll. After takeoff the test aircraft engaged the sidestick control system and made small pitch and roll inputs to insure system stability and to obtain initial pilot comments for that particular configuration. The T-38 then assumed the lead and climbed to 15,000 to 17,000 feet MSL with the test aircraft flying either a loose route or close formation position.

Tracking Tasks. Five tasks were evaluated for each configuration: Close formation, wind-up turns, 3-g turns with rapid reversals, a 2½-g cine-track maneuver, and closed pattern touch and go landings. Three configurations were evaluated on all but three sorties, which were limited due to system malfunctions. Rudder was used on only the close formation and cine-track maneuvers. Each task was repeated until the test aircraft pilot was satisfied with the evaluation.

Formation. Prior to assuming the close formation position after a configuration change, a quick evaluation of the aircraft's pitch and roll response, stick force gradients and stick deflection was made in the extended trail position. The test aircraft then assumed a close formation position. Wing tip clearance was maintained as was nose/tail separation in case of NT-33 flight control system malfunction. The target aircraft then performed a series of modified lazy-8 maneuvers with up to 90 degrees of bank within an airspeed range of 180 to 350 KIAS. Each formation evaluation also included at least one wind-up turn of up to 3½-g's.

Wind-Up Turn. The project pilot dropped back 1500 feet behind the target aircraft as determined by sight picture. When the project pilot indicated ready, the target pilot began a constant speed (280 KIAS) slowly increasing G (approximately 0.2 G/sec) turn, up to a maximum of 3.2-g's (where moderate buffet occurred). The project pilot aggressively tracked the target aircraft's forward canopy throughout this maneuver, using a gunsight depression of 0 mils to help eliminate pendulum effects.

Constant-G Reversals. After completing the wind-up turn, the project pilot again positioned his aircraft 1500 feet behind the target aircraft. The target aircraft then established a 3-g turn, maintaining airspeed between 280 to 300 KIAS. Upon a call from the test aircraft, the target would then execute a rapid unloaded reversal. The test aircraft would delay 3 to 4 seconds, then reverse and rapidly reacquire and track the target.

Cine-Track Maneuver. Having completed the constant-g reversals, the project pilot would stabilize 1500 feet behind the target aircraft. The target aircraft would then begin a constant 280 KIAS, 2½-g turn. On the project pilot's call, the target aircraft would perform a constant 2½-g barrel roll through 540 degrees of roll. After completing the roll the target aircraft would continue the 2½-g turn at 280 KIAS and repeat the barrel roll on the project pilot's call. At the end of this set of maneuvers, the safety pilot would perform an in-flight debriefing of the project pilot. The project pilot would then begin the set of tracking tasks with the next configuration.

Landing Tasks. Each configuration was examined during closed traffic patterns with touch and go landings. The first pattern was flown in the conventional manner, using 140 KIAS in the final turn and 130 KIAS on final approach. On the second pattern in each configuration, an intentional base-to-final overshoot and balloon during flare was performed to examine the ease of recovery. The final approach configuration on all approaches was: gear, 30 degrees flaps and speed brake.

Post-Mission Debriefing. Each mission ended with a debriefing conducted by the project engineer who monitored the flight and included the project pilot, target pilot, and the safety pilot. The debriefing was normally conducted immediately after the mission.

TEST RESULTS AND ANALYSIS

Analysis of Configurations.

The Cooper-Harper ratings by themselves (Figure 48), did not identify the particular problems associated with the test configurations. For example, the ratings for two configurations may have both been 5, but one because of over sensitivity and the other because of sluggishness. However, when used in conjunction with the pilot comments (Figure 49), both the problem and its impact could be established. This allowed the determination of the boundaries described in the following paragraphs.

In depth analysis of the pilot ratings and comments revealed four separate boundaries to the region of acceptable handling qualities for air-to-air tasks. Similar boundaries exist for the landing task; however, the acceptable region was somewhat larger. The exact locations of these boundaries may vary with aircraft dynamics, control system dynamics, airspeed, control input prefilters, sidestick geometry, aircraft maneuverability, and pilot physiology; similar boundaries will probably be present in any highly maneuverable aircraft with sidestick controller. Two of the boundaries were based on anthropometric considerations where the sidestick force or deflection exceeded the pilot's wrist capabilities.

Configuration X: 18,C,2,3,2,2,2,3

* NOT EVALUA..D

STICK FORCE GRADIENT	0.18	0.38	0.57	0.73	0.96	1.10
Very Light	2	8 11,B,7,6,8,7,8,*	14 17,A,*,*,*,*,*,3	20	26 1,A,4,6,6,*,*,* 2,B,4,5,5,*,*,* 4,D,4,6,4,7,7,4	32
Light	3	9 9,C,4,5,4,5,5,* 18,C,*,*,*,*,*,4	15 11,B,4,8,7,6,7,5 12,A,3,5,2,3,4,1 16,D,4,4,5,4,4,4 17,A,2,4,2,2,3,*	21 1,A,4,4,4,*,*,2 2,B,5,7,7,*,*,* 3,C,4,5,5,4,5,4 4,D,5,6,5,5,5,2	27 6,B,2,5,3,4,4,* 7,A,4,5,5,4,4,3	33
Medium	4 15,B,4,6,7,5,7,5	10 5,C,4,4,4,4,4,* 8,B,3,6,6,6,5,* 12,A,2,3,2,3,3,4 18,C,3,3,3,4,4,*	16 3,C,2,5,3,3,3,4 8,B,4,6,6,4,5,3 9,C,4,4,5,3,4,3	22 5,C,2,4,3,4,3,2 6,B,4,5,6,6,5,* 7,A,3,5,4,5,5,3 17,A,2,4,4,2,3,*	28 2,B,2,4,5,*,*,* 4,D,3,7,5,7,6,4 9,C,3,4,4,3,4,2	34 14,D,[illegible],4,4,4,4,4 17,A,*,*,*,*,*,7
Heavy	5	11 3,C,3,3,4,3,3,* 8,B,4,6,5,5,5,4	17 5,C,3,4,4,3,4,5 7,A,5,6,4,5,6,*	23 10,D,3,7,7,4,5,* 11,B,2,5,4,4,4,6 18,C,3,4,4,4,4,4	29 14,D,5,3,3,5,5,* 15,B,2,5,3,6,5,* 17,A,5,5,4,5,5,8	35 10,D,3,7,7,5,7,7
Very Heavy	6 12,A,6,6,6,6,6,7	12	18 15,B,4,4,5,4,4,8	24 14,D,4,4,3,4,4,8	30	36

LONGITUDINAL STICK DEFLECTION GRADIENT (deg/Lb)

Legend: Sortie No., Pilot, Formation, Acquisition, Tracking, Cine Track, Overall Air-to-Air, Landing

FIGURE 48 Overall Cooper-Harper Ratings (Raw Data)

FIGURE 49 PILOT COMMENTS

General Comments:

(1) Hitting stick deflection stops before running out of pitch or roll authority (i.e., changing from motion to pressure cues) was very objectionable.

(2) More precise tracking capability was apparent with small motion cues rather than strictly pressure cues.

(3) The ± 10 mil lateral oscillation of the NT-33 was very objectionable during all evaluations.

(4) The heavy rudder forces and very limited rudder pedal movement was very objectionable.

(5) Pilots desired that the throttle and stick be symmetrically located.

Pilot Codes:

A = Daniel
B = Thiel
C = Saxon
D = LaBarge

Configuration # 4: (B)

(1) Control harmony OK in formation but was a problem in cine-track.

(2) Too sensitive - continuous pitch bobble and wander - unable to attain a tracking solution. Laterally too sensitive in formation.

(3) Overshoots in pitch and roll during acquisition tasks.

(4) Use of rudder helps cut lateral pipper wander.

Configuration # 6: (A)

(1) Formation: sluggish, slow roll response, force too high (laterally). Longitudinal forces too high. Stiff stick.

(2) Tracking good once pipper on target but corrections difficult due to sluggish response.

(3) Fatiguing without use of trim.

(4) Used knee to get desired roll response to the right.

(5) Sensitivity too low, harmony OK but too stiff.

(6) Safety observer's comment - "One of the best performing configurations observed once target acquired."

Configuration # 8: (B)

(1) Very poor harmony.

(2) Constant lateral oscillation in formation plus pitch bobble.

(3) Lateral oscillation could be dangerous.

(4) Controllability in question under very heavy workload due to very bad lateral oscillation during tracking.

FIGURE 49 (continued)

Configuration # 9: (C)

(1) A little too sensitive laterally.
(2) 5 to 6 mil pitch and roll oscillations during fine tracking - a little too sensitive in both axes.
(3) Lateral overshoot tendency.
(4) Forces a little heavy in landing pattern, but overall acceptable in the pattern.

Configuration # 10: (A,B,C)

(1) Slight pitch bobble ($\pm$4 mils).
(2) No PIO tendencies.
(3) Rapid roll inputs require too much force, max roll rates too slow.
(4) Need lighter stick forces to the right than to the left.
(5) Only pilot C felt it was too sensitive.
(6) Small overshoots in pitch during gross acquisition.

Configuration # 11: (B,C)

(1) Acceptable, but had a very slight pitch bobble in fine tracking tasks.
(2) Lateral pipper wander gave the most problem in tracking.
(3) Much less sensitive in roll than pitch, increasing workload to make fast rolls. In landing task, stick was a little stiff and heavy with pitch PIO tendency.
(4) Control harmony hampered accurate tracking.
(5) Pilot B felt that the rudder helped during cine-track, but that the forces were too high (stick).

Configuration # 14: (A, landing task only)

(1) Very sensitive aircraft, but acceptable.
(2) Light stick forces could lead to secondary stall, balloon during flare, and takeoff over-rotation tendencies.

Configuration # 15: (A,B,D)

(1) Stick forces a little too light in pitch. Tendency to overshoot longitudinally.
(2) $\pm$4 mil longitudinal pipper bobble. Pitch sensitivity decreased by using some forward trim.
(3) Lateral forces a little too heavy. Difficult to get roll rates established or stopped. Good for fine tracking, but poor for gross acquisition.
(4) Poor control force harmony. Landing task assigned Cooper-Harper of 1. (A)
(5) Seemed to have pitch and lateral stick force lightening.

Configuration # 16: (B,C)

(1) Difficult to acquire target due to pipper wander.
(2) Control harmony poor in tracking tasks, acceptable in formation.
(3) Pitch bobble and lateral wander during tracking.

FIGURE 49 (continued)

(4) Harmony not as much of a problem when using rudder during cine-track.
(5) Longitudinal stick force vs. deflection too high in landing flare. Mild roll PIO on touch & go landings.

Configuration # 17: (A,C)

(1) Stick was heavy.
(2) No pitch bobble was noticed.
(3) Lateral forces much too heavy, especially when trying to quickly reverse.
(4) Some directional drift apparent when tracking and tendency to overshoot directionally during acquisition.
(5) Felt insensitive and sluggish in landing tasks. Lateral PIO tendency.

Configuration # 18: (B)

(1) Trim continually required to reduce forces in formation.
(2) Control harmony OK.
(3) Pitch very nice in tracking (5 mil maximum excursions), but had 10 to 20 mil lateral pipper wander.
(4) Lateral axis is the only problem in tracking.
(5) Acquisition task not bad but some overshoot in both pitch and roll.
(6) Rudder completely eliminated wander.
(7) Longitudinal force much too heavy - very sluggish in pitch and roll. Full aft stick required in flare.

Configuration # 21: (A,B,C,D)

(1) Too sensitive in both axes - PIO tendency.
(2) Control harmony not good.
(3) Bad overshoots both in pitch and roll during acquisition.
(4) Pitch bobble (6 to 8 mils) and annoying wander during tracking, helped somewhat by rudder.

Configuration # 22: (A,B,C)

(1) Control harmony was good.
(2) Slight tendency to overshoot in pitch during gross acquisition in heavy workload environment (pilots B & C only).
(3) A & C thought pitch was just a little sensitive. B thought it too sensitive.
(4) Roll forces were too high and should be a little lighter.
(5) In landings, controls slightly sluggish. Harmony was OK. Pilot A reached aft stop on landing and felt the stop indicated he had ran out of pitch control - very objectionable. Too much stick motion.

Configuration # 23: (B,C,D)

(1) Fine tracking OK once established, but gross acquisition was difficult due to high stick forces.
(2) Stick forces too high. Must horse airplane around as it responds too slowly. Sluggish responses.

FIGURE 49 (continued)

(3) Poor responses in landing pattern. Very heavy forces. Hard to start and stop roll rates. Hit aft stop at touchdown which was very objectionable. Stick deflections too large.

Configuration # 24: (D)

(1) Feels rubbery in formation - difficult to predict response in both axes, especially pitch. Longitudinal stick deflection too high.

(2) Pitch PIO apparent when tracking under G load. 5 to 10 mil pipper wander but no overshoot in either pitch or roll during acquisition.

(3) Controls felt too stiff.

(4) Fast roll produces ratcheting.

(5) Forces and deflections too high in both axes.

(6) Landing in high crosswind difficult due to lack of response. Unstable spiral mode apparent due to necessity to hold large opposite aileron force in turns in pattern. Controllability in question.

Configuration # 26: (B,D)

(1) Lateral sensitivity too great - lateral PIO tendency.

(2) Large lateral overshoots.

(3) Poor control force harmony.

Configuration # 27: (A,B)

(1) Pitch was too sensitive.

(2) Lateral wander was present, but was not as pronounced as the pitch bobble.

(3) Roll oscillations & overshoot were present during gross acquisition.

(4) Compensation required was moderate to high during tracking.

(5) Pilot A thought that pitch was too sensitive in formation, but pilot B liked it.

(6) In the landing tasks, pitch was too sensitive, control harmony was good, forces were light, and there were no lateral problems.

Configuration # 28: (B,C,D)

(1) Good in formation - however, slight pitch bobble when trimming due to the sensitive stick being affected during trim button operation.

(2) Good control force harmony.

(3) Overshoots in both axes during gross acquisition - both axes a little too sensitive - difficult to prevent overshoots.

(4) Mild pitch and lateral bobble during tracking.

(5) Difficult to precisely predict response in both axes.

(6) Stick forces too light in both axes.

(7) In landing tasks, full aft stick used at touchdown, but pitch control was nice. Too sensitive laterally on final.

FIGURE 49 (continued)

Configuration # 29: (B,D)

(1) Formation - no adverse comment - comfortable, easy to stay in close.
(2) Tracking under G-load - 3 to 4 mil pitch bobble. Requires pitch trim to keep force gradient comfortable.
(3) Slight directional overshoot in gross acquisition - good in pitch, very responsive and had good feel.
(4) Control harmony very nice, sensitivity OK.
(5) Lateral wander in cine-track not helped much by use of rudder. Using rudder causes overshoots.
(6) Hit lateral stops when attempting to roll quickly - deflections too large in both pitch and roll.
(7) Only really objectionable characteristic is that stick motions are too large in both axes.

Configuration # 33: (D)

(1) Too sensitive in pitch. 5 to 8 mil bobble during fine tracking. Pitch overshoots during gross acquisitions.
(2) Control harmony satisfactory.
(3) Hard to make precise corrections in pitch or roll.

Configuration # 34: (A,D)

(1) Stick felt loose. Excessive deflections required.
(2) Too much aft stick required to increase G.
(3) 5 to 10 mil pitch bobble during fine tracking.
(4) During landing tasks, far too much motion required. Hitting stops gave the impression of a lack of adequate control authority. Pitch control jerky with stick against stop during flare. Very high stick forces throughout pattern.

Configuration # 35: (D)

(1) Pitch sensitivity OK, but was laterally stiff.
(2) Lateral overshoots & sluggish ailerons prevented desired performance levels.
(3) Pitch control good during fine tracking, but had mild overshoots during gross acquisition tasks.
(4) Poor control force harmony - felt like higher lateral force gradient than longitudinal.
(5) In landing task, lateral axis was satisfactory. However, pitch axis was bad as stick forces were too high and excessive deflection was required. Very sluggish pitch response that required improvement.

Configuration X: (C)

(1) No overshoot or wander tendencies.
(2) No pitch or roll compensation required.
(3) Easy to control, comfortable, good performance.
(4) Excellent for fine tracking and gross acquisition maneuvering.
(5) Best configuration evaluated, comfortable in landing pattern.

The other two boundaries were determined by the man-in-the-loop dynamics where the closed loop system became too sluggish or marginally unstable. Each boundary will be discussed in greater detail in following sections. A near optimal configuration was chosen based on pilot comments and evaluated once on the last data sortie. Pilot comments confirmed that this configuration was superior to all others tested.

Excessive Force Boundary.

When presented with very heavy force gradients, evaluation pilots commented that trim was required to obtain comfortable elevator stick forces while maneuvering. The very heavy force gradient requires approximately 20 lb of pull force to obtain 4 g's. The evaluation pilots found it difficult to make the fine corrections required during the terminal acquisition and tracking phases while maintaining the required 10 to 20 lb pull force (2.3 - 4 g's). In some cases, the evaluation pilots felt that the heavy force gradient required excessive force. For aircraft with higher limit load factors, an even lighter force gradient may be necessary to avoid trimming the aircraft in the maneuver. All members of the test team feel that during air combat, the pilot should be able to accurately track a target up to the limit load factor without trimming or encountering excessive control forces. Therefore, an excessive force boundary was established at the heavy force gradient.

Excessive Deflection Boundary.

When the pilot's commanded input produced sidestick deflections of approximately 20 degrees (full throw), the evaluation pilots complained about excessive wrist bending or the distraction from the stick hitting the stop. The cramped wrist problem could be alleviated by repositioning the forearm on the arm rest, however this was also distracting and fine control was temporarily lost. When the stick contacted the motion stop, the pilot could still command additional pitch (or roll) due to the force-command system; however, the pilots found that they could no longer make precise corrections without stick motion. All evaluation pilots felt that the stick motion stops should never be encountered within the operational envelope of the aircraft. Furthermore, the pilots had no difficulty determining when stick motion ceased. Therefore, the motion stops might be used as an additional tactile cue to the pilot (i.e., limit load factor, AOA, or roll rate). The evaluation pilots felt that the 20 degrees maximum deflection was adequate; however, anthropometric data should be used to establish the maximum allowable stick deflection for operational aircraft. A deflection boundary was established where the stops were encountered at 4-g's for air-to-air tasks and in the flare during landing tasks.

Sluggishness Boundary.

When the combined stick force and motion exceeded this boundary, the evaluation pilots described the aircraft as slow, sluggish, or rubbery feeling for the test conditions. This boundary was less restrictive

than the force and deflection boundaries described above. Typically, the sluggish airplane tended to wander off target when tracking. During acquisition, the airplane would be very slow to get on target or overshoot the target depending on the compensation and adaptation level of the pilot. The sluggish configurations were stable and good tracking could be accomplished with the target in a constant G turn; however, gross acquisition was difficult and the pilots tired quickly. When the pilot attempted to evaluate the aircraft's pitch response with a sinusoidal stick pump, the apparent short period, closed loop pitch response, was quite slow. In formation, the pilots tended to fly further out with sluggish configurations. The test team feels that configurations with sluggish response are not suitable for air combat.

Sensitivity Boundary.

When the stick force gradient and motion cues were insufficient, the pilots described the aircraft as too sensitive. Pilot induced oscillation tendencies were apparent, particularly during high gain tasks. The aircraft responded very quickly and the apparent short period, during sinusoidal stick pumping, was very fast. In general, the pilots liked the quick crisp response for configurations just inside this boundary; however, residual pitch bobble was present during tracking, and the pilots tended to overshoot (especially in roll) during acquisition. The pilots described this roll overshoot as an apparently underdamped roll mode. Pilot comments indicated nose down trim would reduce the longitudinal PIO tendency. However, in the opinion of the test team pilots it should not be necessary to apply nose down trim to eliminate a longitudinal PIO tendency. For configurations outside this boundary, the evaluation pilots found that the PIO tendencies were considerably worse. During the initial sorties, pilots with little air-to-air tracking experience found the very sensitive configurations particularly objectionable. The pilot's ability to compensate for the high sensitivity increased with sidestick experience; however, the test team felt that the overly sensitive region should be avoided. The sensitivity boundary could be greatly influenced by the aircraft and control system dynamics and the control input prefilter.

Configuration X.

The last two data sorties were used to verify the conclusions concerning sensitivity and to identify an optimal configuration. On data sortie 17, configurations 15, 22 and 29 were evaluated in sequence. The pilot felt that although good performance was attainable, configuration 15 was slightly too sensitive and configuration 22 was slightly too sluggish. In addition, the lateral stick deflection stops were encountered during reversals in configuration 22. The pilot commented that he felt that something midway between 15 and 22 would be optimal. Configuration X was chosen approximately halfway between 15 and 22. On the last data sortie, configurations 10, X and 23 were flown in sequence. That pilot found configuration 10 slightly too sensitive and configuration 23 sluggish;

however, he was quite emphatic when he stated that configuration X was the best he had encountered. Therefore, the test team feels that the optimum configuration is very close to configuration X.

When these boundaries are analyzed together, they define a region within which acceptable elevator axis response exists. As shown in Figures 50 and 51, this region is elongated from lower left to upper right. Pilot ratings and comparative comments were a function of the direction of change from one configuration to the next. If the change was done along this elongated axis, the pilot saw little variation until large changes were made. That is, if the deflection gradient (deg/lb) and the force gradient (g/lb) were decreased together, than the change in handling qualities appeared very small to the pilot. However, if one was increased and the other decreased, then the change in sensitivity was readily apparent; even with small changes in the gradients.

Although configuration X is near the center of the acceptable region, the optimum configuration may shift slightly with variations in control harmony. The test team feels that the optimum will remain inside that region, but work should be done to optimize the lateral and directional axes.

The pilot comments proved to be the best data for evaluating the configurations. As a result of the chronological sequence of test configurations, large changes in the overall acceptability of configurations were seldom encountered on the same flight. Frequently, the pilot would dislike several configurations equally; but, for entirely different reasons. Highly objectionable behavior on one axis tended to mask minor problems in the other axis. The control harmony was nearly constant for all test configurations; however, the pilots reported excellent control harmony for some configurations and harmony problems for others. Apparently, the pilots perception of harmony is not linear. Increased force or deflection would decrease the sensitivity of a configuration. Fine tracking accuracy during wind-up turns did not always reveal good configurations. Several configurations which produced good tracking were too sluggish for acceptable gross acquisition capability.

Analysis of Tasks.

All pilots felt the test maneuvers selected were adequate to obtain the desired results. Initial examination of a given configuration was made in an extended trail position. Close formation then examined configuration comfort in terms of control harmony, control response and sensitivity, and concentration required in a normal environment. The wind-up turn provided information about longitudinal bobble, PIO tendencies, and fine tracking capabilities. The reversals provided good information about roll and pitch response, lateral and longitudinal overshoot and PIO tendencies and gross acquisition capability. The cine-track maneuver then re-examined all these parameters and the effect of using rudder to assist in achieving desired results. The landing task was then used to

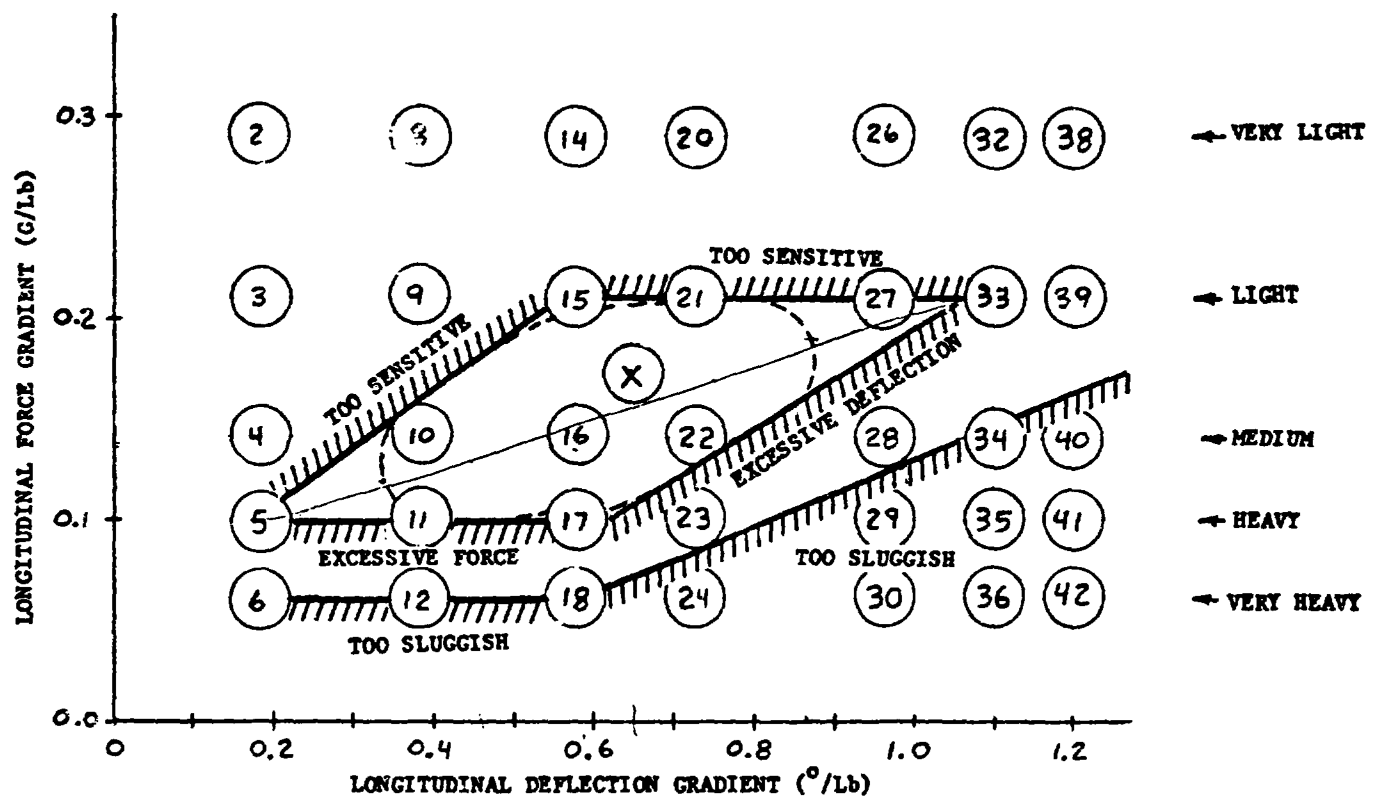


FIGURE 50 Fo~ ı and Air-To-Air Tracking Results

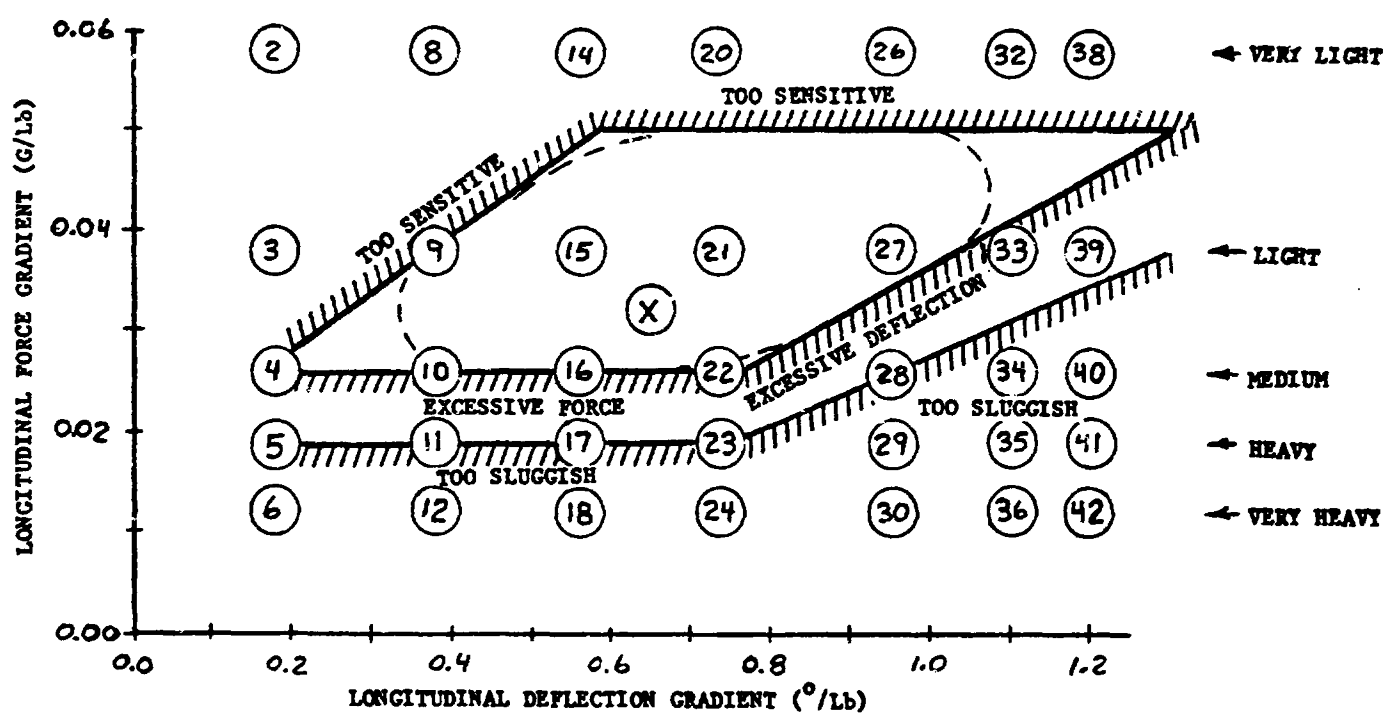


FIGURE 51 Landing Task Results

re-examine each control configuration in a low speed, low altitude, power approach condition to determine if a given configuration was suitable for several totally different tasks.

The test team members further felt that the optimal area of stick motion and stick force gradient was determined for the given aircraft dynamic characteristics. It was felt that similar testing should be accomplished with various dynamics configurations to determine the effects of aircraft dynamics changes on pilot ratings of given control configuration. Additional testing should also be accomplished on air-to-ground tracking tasks.

All test maneuvers were flown without the use of the rudder except for the cine-track maneuver. This was done to remove one variable which would have possibly masked deficiencies in the other two axes which would otherwise be apparent. Conversely, the test team pilots felt that acquiring and tracking without the use of rudder was unrealistic in a "real world" sense. It was therefore concluded that once the rudder force/deflection gradients in the NT-33 are optimized that all tasks should be flown both with and without the use of rudder. It would thus be possible to determine the effect on pilot ratings of using rudder.

Analysis of Pilot Factors.

Throughout the test program, certain pilot factors were found to influence the ratings of the different configurations and, in some cases, the pilot's opinion of the configuration. Initially, they were most influenced by the pilot's background. This became less of a factor as each pilot became more proficient at the tasks, and the opinions and ratings became more comparable between any two pilots. It was evident that at least two practice sorties with the sidestick controller were necessary for each evaluation pilot before achieving comparable results. None of the project pilots had ever flown sidestick equipped aircraft before this program, but all pilots thought that the sidestick is superior to the center stick for these type tasks.

Available sidestick deflection became a factor which affected pilot opinion of certain configurations. If a pitch stop was reached, the pilot's immediate impression was that he had no more elevator authority, even though more force could command more pitch. This was not a factor with light force gradients or small deflection gradients.

The lateral control force gradients were the same for left and right roll. This was acceptable for the lighter force gradients, but commanding right roll was more difficult than left roll with heavier force gradients. The possibility of different gradients left and right should be investigated.

The pilots found that better pitch control was available if they were holding moderate back force while tracking. Pilot comments indicated that the heavier gradients would require nose up trim, while tracking with lighter gradients might be improved with nose down trim. Neither was felt

to be satisfactory, as each resulted in a higher workload. Of significance in this comment, however, is the idea that a poor configuration might be made to appear acceptable during certain tasks by the use of trim.

An annoying characteristic of the NT-33A was the lack of symmetry between the throttle and the sidestick in position, motion required, and forces required. These should be optimized for better harmony and reduced workload.

Finally, the rudder forces were too high for most configurations during the cine-track maneuver. This lack of harmony between the sidestick and rudder affected some ratings and increased the workload. Better rudder harmony could possibly increase the envelope of acceptable handling qualities.

CONCLUSIONS AND RECOMMENDATIONS

The primary objective of this test program was achieved in that the influence on pilot ratings of varying sidestick force and deflection gradients was determined. For the specific aircraft and control system dynamics used, boundaries were determined which define the region of acceptable handling qualities. The secondary objectives of quantitatively verifying pilot tracking performance and investigating control harmony were not achieved due to instrumentation malfunctions and aircraft maintenance problems which resulted in the loss of a significant number of data sorties. The test team did not consider the lack of quantitative tracking data a significant deficiency. However, the test team felt that control harmony variation is a fertile area for future test efforts.

None of the evaluation pilots had previously flown a sidestick configured aircraft and all pilots involved considered the sidestick to be superior to the centerstick controller for air combat maneuvering. Further, a nearly optimal control configuration was identified.

For a highly maneuverable aircraft with a sidestick controller, the region of acceptable handling qualities will be bounded by limits of excessive force, deflection, sensitivity and sluggishness. The location of these boundaries may vary with airframe and control system dynamics, control input prefilters, sidestick geometry, aircraft maneuverability, and pilot physiology and adaptation. The force gradient should be such that the pilot could accurately track a target up to the limit load factor without encountering excessive control forces or the need to trim. For a sidestick with motion, the motion stops should never be encountered within the operational envelope. However, motion stops can be used to provide tactile cues at the extremities of the envelope. Keeping in mind that control harmony was kept constant throughout the test, analysis of pilot comments further showed that the pilots' perception of control

harmony was not linear. Maximum stick motion should not exceed the physiological limits of the pilot's wrist and anthropometric data should be used to establish the maximum allowable stick deflection for operational aircraft.

When the stick force gradients were too small and the deflection gradients too large, the closed loop pilot-aircraft system was sluggish and slow to respond. Although sluggish configurations frequently produced good fine tracking performance they were judged not suitable for a fighter aircraft due to the difficulties encountered in gross acquisition. When both force and deflections gradients were reduced simultaneously, pilots detected only slight variations in handling qualities. Pilots reported those configurations wherein the force gradient was increased and deflection gradient decreased to be much more sensitive to control inputs. However, when force gradients were increased and deflection decreased beyond certain limits, the closed-loop system became overly sensitive and pilot induced oscillations resulted. Pilot comments suggested that by trimming to reduce or increase stick forces to a more comfortable level it may be possible, in some cases, to improve tracking accuracy.

During the course of this evaluation several conclusions were drawn which may also apply to other, similar evaluations. Pilot comments provided the best data for evaluating the various configurations. Cooper-Harper ratings, by themselves, were a poor data source. However, when used in conjunction with pilot comments, they were useful in establishing the relative impact of a given problem. Highly objectionable behavior in one axis tended to mask problems in the other. Due to pilot variability and adaptation, a statistical analysis of Cooper-Harper ratings would require a large number of evaluations of each control configuration to achieve an acceptable level of significance.

Initially, pilot ratings and comments were strongly influenced by background and training (Figure 52). This factor became less significant, however, as proficiency in flying the maneuvers and adaptation to the environment increased. Ratings and comments of the project pilots converged dramatically at the end of the test program. Each flew at least two sorties before comparable results were achieved. The value of quantitative data from relatively benign maneuvers such as constant G and wind-up turns is questionable; several very sluggish configurations which were totally unsuitable for a fighter aircraft produced excellent fine tracking characteristics.

The test team felt that the following areas should be investigated during future sidestick controller evaluations:

1. As previously mentioned, anthropometric data should be used to establish stick deflection limits for operational aircraft with sidestick controllers.

2. Variations in lateral-directional control harmony should be investigated.

FIGURE 52 PILOT BACKGROUND INFORMATION

PILOT A:

F-100D/F - 500 hours, SEA combat tour
Mission: Air-to-ground and escort
F-4C/D/E - 1350 hours
Mission: Air-to-air and air-to-ground (conventional and nuclear)
Graduate of USAF Fighter Weapons School. Extensive experience in air-to-air environment

PILOT B:

T-38 - 1200 hours total, 800 IP
C-130A/E - 585 hours (no combat time)
T-39 - 140 hours (VIP airlift)
No air-to-air experience prior to TPS
(also, 800 hours of light aircraft time)

PILOT C:

A-1E/H - 190 hours - SEA combat tour
Mission: Air-to-ground and escort (conventional)
O-2A - 650 hours - SEA combat tour
Mission: Forward air controller
T-38 - 1200 hours, 1000 IP
T-39 - 100 hours (VIP airlift)
No previous air-to-air experience

PILOT D

KC-135A - 1400 hours (500 IP)
Mission: World-wide air refueling (all types)
C-123K - 950 hours - SEA combat tour
Mission: Medium assault airlift (primitive airfields in forward areas, cargo and troop transport)
T-39 - 100 hours (VIP airlift)
No prior air-to-air experience

3. The possibility of differing gradients for left deflections versus right deflections should be investigated.

4. Additional testing should be accomplished on air-to-ground tracking tasks.

5. Testing should be accomplished wherein aircraft dynamics are varied with control ratios held constant to determine the effects of such variation on pilot ratings of a given control configuration.

APPENDIX D

TECHNICAL RESULTS AND DISCUSSION FROM USAF TEST PILOT SCHOOL LETTER REPORT - 5 July 1978 "Limited Flight Evaluation of the Effect of First Order Prefilters on the Handling Qualities of Sidestick Controlled Aircraft" by Gregory V. Lewis, Captain, USAF; Douglas M. Carlson, Captain, USAF; George J. Cusimano, Captain, USAF; Menahem Shmul, Captain, IAF and Thomas V. Tilden, Captain, USAF.

ABSTRACT

A limited investigation was conducted to determine the impact of varying the corner frequency of a first order, lag prefilter in the longitudinal and lateral axes of a sidestick controller for fighter aircraft. The test aircraft, AFFDL's variable stability NT-33A, was configured with the open loop dynamics of a high performance fighter similar to an F-16. The results indicate an identifiable preference for a particular prefilter for two out of the three tasks evaluated. Additionally, varying the amount of sidestick force and deflection changed the preferred prefilter. Data presented included pilot comments, pilot preferences, fine tracking performance, and Cooper-Harper ratings. These data can be used to further expand the data base on sidestick control configurations generated in previous evaluations of this type. Data, target support, practice, and calibration flights totalling 46 sorties and 65 flying hours were flown at the Air Force Flight Test Center, Edwards AFB, California from 15 May 1978 to 9 June 1978.

TEST METHODS AND CONDITIONS

The test was conducted in two phases. Phase I was designed to examine the effects of large variations in prefilter corner frequencies on one stick force/deflection and to determine the range of corner frequencies to be used in Phase II of the test. Phase II testing was to answer the specific objectives previously listed.

Phase I consisted of varying the corner frequency of the prefilter while keeping the stick force/deflection constant. The corner frequencies tested were 2, 4, 8, 12 and 16 radians per second. The force/deflection configuration used was that recommended as best during the previous tests (References 2 and 3) as shown in Table VIII, point A. The same prefilter was used in both the longitudinal and lateral axes. Phase I consisted of four sorties.

In Phase II, both the corner frequency of the prefilter and the stick force/deflection characteristics were varied. The prefilter corner frequencies selected were 2, 8 and 16 radians per second. These corner frequencies were selected because the pilot evaluations of the prefilters during Phase I showed little variation in preference with smaller variations in frequency. The stick force/deflection combinations which were used are points A and B on Table VIII. Again, large variations in the force/deflection combinations were selected in order to increase the likelihood of more discernible differences in overall prefilter and stick combinations. Phase II consisted of 15 sorties.

Throughout the test each combination of force/deflection and prefilter was flown approximately seven times. On each sortie three configurations were evaluated. The test points for a particular sortie were chosen so as to minimize in-flight bias resulting from the order the points were flown.

Mission Description.

Each mission consisted of the following phases:

a. Premission briefing

b. Before takeoff

c. Takeoff and join-up

d. Air-to-air tracking

    1. Constant "g" turn and reversal

    2. Wind-up turn

    3. Lazy eight

e. Recovery and landing

f. Debriefing

TABLE VIII

TEST CONFIGURATIONS

	A		B	
	Longitudinal	Lateral	Longitudinal	Lateral
Force Gradient	.167 g/lb	7 deg/sec/lb	.167 g/lb	7 deg/sec/lb
Deflection Gradient	.7 deg/lb	1.05 deg/lb	.2 deg/lb	.3 deg/lb

Corner Frequencies: 2 radians/second

4 radians/second *

8 radians/second

12 radians/second *

16 radians/second

*Phase I only.

Note: For the landing task, the force gradients were 20% of the air-to-air force gradients shown. The deflection gradients were unchanged.

Premission Briefing.

Premission briefings began at least one hour and a half before takeoff. The target aircraft was piloted by a project pilot to standardize target maneuvers. Project engineers flew in the rear cockpit of the target aircraft. Evaluation pilots were not briefed on configuration parameters to prevent biasing results.

Before Takeoff.

After engine start, the evaluation pilot performed a normal stability and control ground block which was recorded on magnetic tape. Before taking the runway, the evaluation pilot centered the pipper on a target positioned on the south side of runway 22. The gun camera was used to determine camera boresight error.

Takeoff and Joinup.

Both aircraft used standard local area procedures in accordance with AFFTC Manual 55-2. The NT-33A safety pilot made the initial takeoff and the target aircraft took at least 10 second spacing. Joinup and climb-out to 14000 feet MSL was accomplished at 280 KIAS. During climb-out, the safety pilot configured the aircraft for the first test configuration, and transfered control to the evaluation pilot. After level off, an elevator and a rudder doublet were recorded on magnetic tape. The lead was then passed to the target aircraft. Prior to testing each configuration, the evaluation pilot performed small coordination maneuvers to adjust to the new configuration.

Air-to-air Tracking.

Constant "g" turn and reversal. The target aircraft established a 300 KIAS, 30° banked, level turn at 14000 feet MSL. The evaluation pilot stabilized cospeed at 1500 to 2000 feet behind the target. Following "READY" calls from both the target and tracker, the target rapidly increased the bank to maintain 2.0 "g's" without changing airspeed or power setting. With 55 mils set in the fixed gunsight, the evaluation pilot delayed until the target was offset 100 mils and then aggressively positioned the pipper in the middle of the target aircraft exhaust nozzles. The evaluation pilot did not use rudders or trim during tracking. After approximately 20 seconds of fine tracking, the evaluation pilot called "REVERSE" at which point the target pilot rapidly reversed nose high and the evaluation pilot again delayed 100 mils before reacquiring. The gross acquisition and fine tracking were reaccomplished in the new direction. The exercise was terminated at the call of "KNOCK IT OFF".

Wind-up turns. This maneuver was set up the same way as the constant "g" turn. After the standard initiation calls, the target aircraft maintained 300 KIAS and slowly increased bank angle so as to increase "g" at a rate of approximately 0.2 "g" per second up to a maximum of 4 "g's". The target pilot slowly increased RPM so as to reach military power as he reached 4 "g's". Tracking was accomplished as in the constant "g" maneuver. The exercise terminated at 4 "g's", when the target reached heavy buffet,

or at the call "KNOCK IT OFF". This maneuver was accomplished in both directions.

Lazy eight. The target aircraft established level flight at 320 KIAS and 13000 feet MSL and transmitted the direction of his first turn to the evaluation aircraft. The evaluation pilot stabilized 1500 to 2000 feet behind, slightly below, and inside in the direction of turn. After the standard initial calls, the target executed a lazy eight maneuver. The target pilot held a constant 2.2 "g's" throughout the maneuver, attaining the minimum airspeed of 250 KIAS when reaching approximately 90° of bank and turn. At 180° of turn, the maximum airspeed of 320 KIAS was reached as the target brought his wings to level. The maneuver was continued in the opposite direction. In order to maintain the desired separation, the target increased power approximately 5% while decending and decreased power a like amount while ascending. Tracking was accomplished as in the constant "g" maneuver.

Recovery and Landing.

The task evaluated during this phase of flight was the ability to attain and control the pitch attitude during the flare and touchdown. The evaluation pilot accomplished at least one landing in each configuration tested during the air-to-air portion of the flight. If two landings were performed, the first was with a normal approach while the second was offset from centerline to increase the task difficulty. The pilot evaluation and the configuration change were accomplished in level flight while entering the pattern for another landing. Either overhead or straight-in approaches were flown, ensuring that final approach was at least one mile long. No attempt was made to accomplish a precision glide path or spot landing.

Debriefing.

As soon as possible after each flight, a debriefing was conducted using a detailed debriefing guide. As a minimum, the debriefing included the crewmembers from both aircraft.

RESULTS AND ANALYSIS

Four data sources were used to evaluate test results. Cooper-Harper pilot ratings were given after all air-to-air or landing tasks were completed in each configuration and are summarized in Figures 53 through 58. Pilot comments on each configuration were recorded in flight and are summarized in Figure 59.

Although the Cooper-Harper ratings assigned to the various configurations almost always fell in the range of 4 to 7, it was found

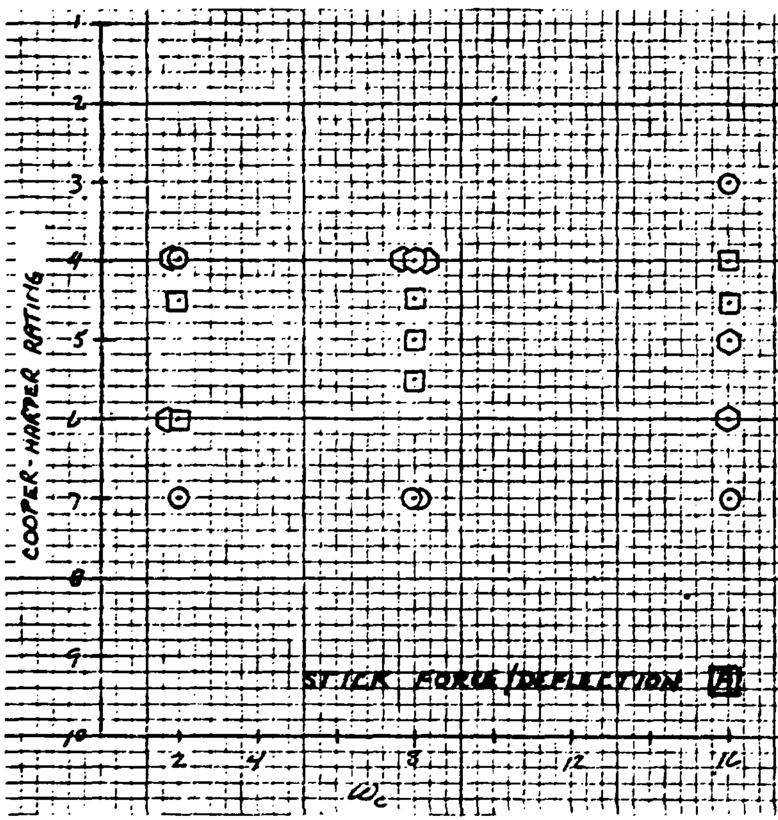


FIGURE 53 Cooper-Harper vs ω_c
Gross Acquisition

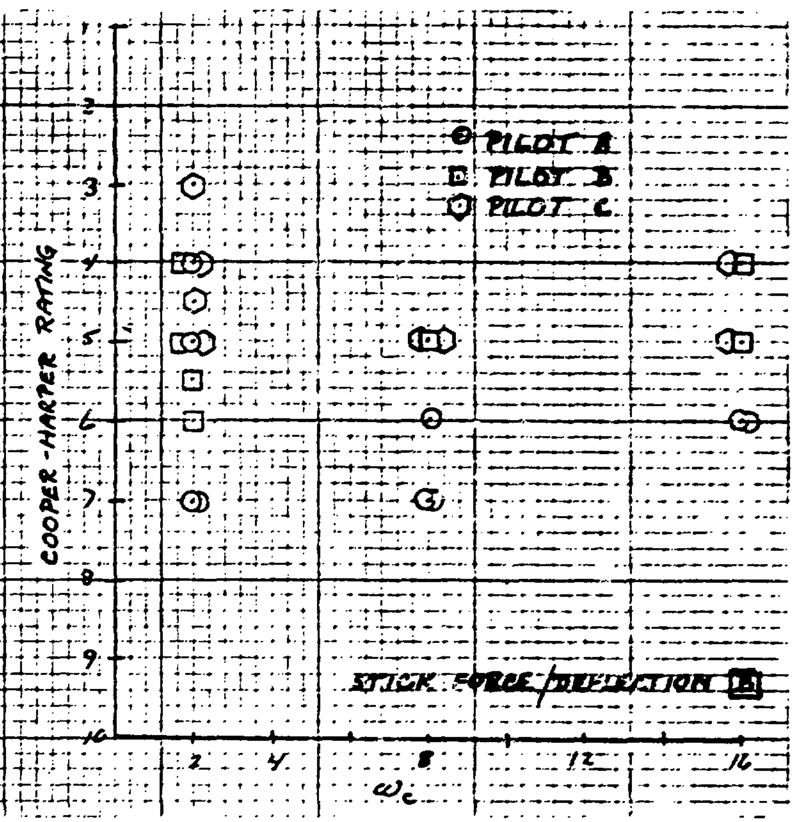


FIGURE 54 Cooper-Harper vs ω_c
Gross Acquisition

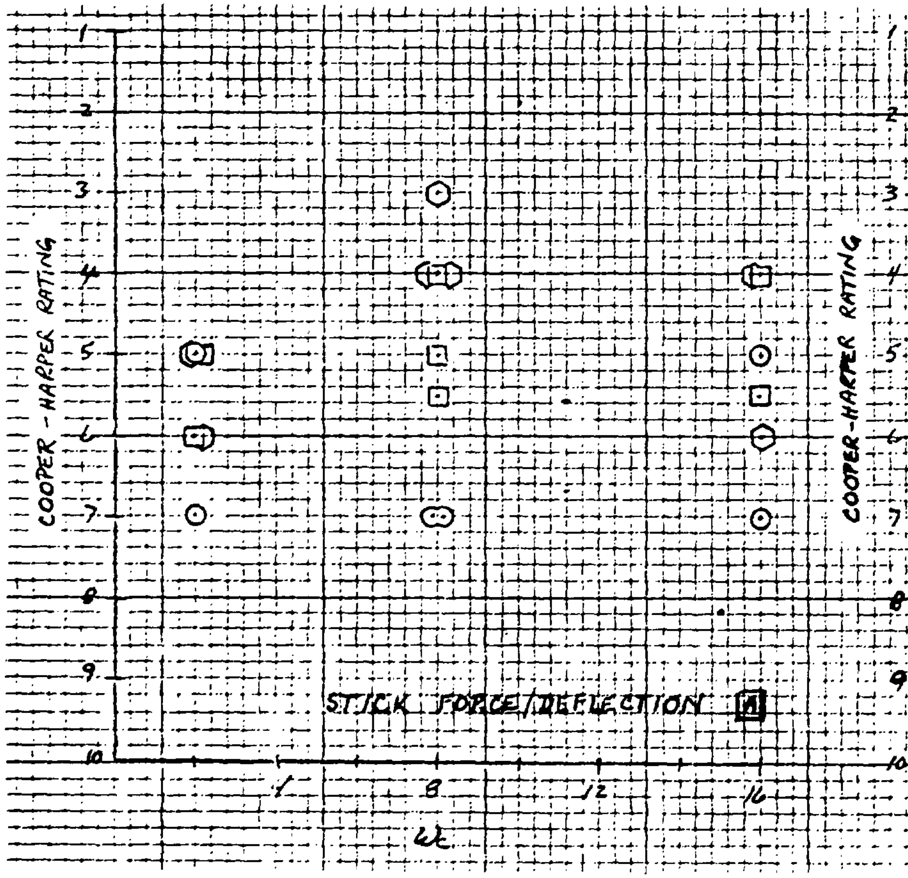


FIGURE 55 Cooper-Harper vs ω_c
Fine Tracking

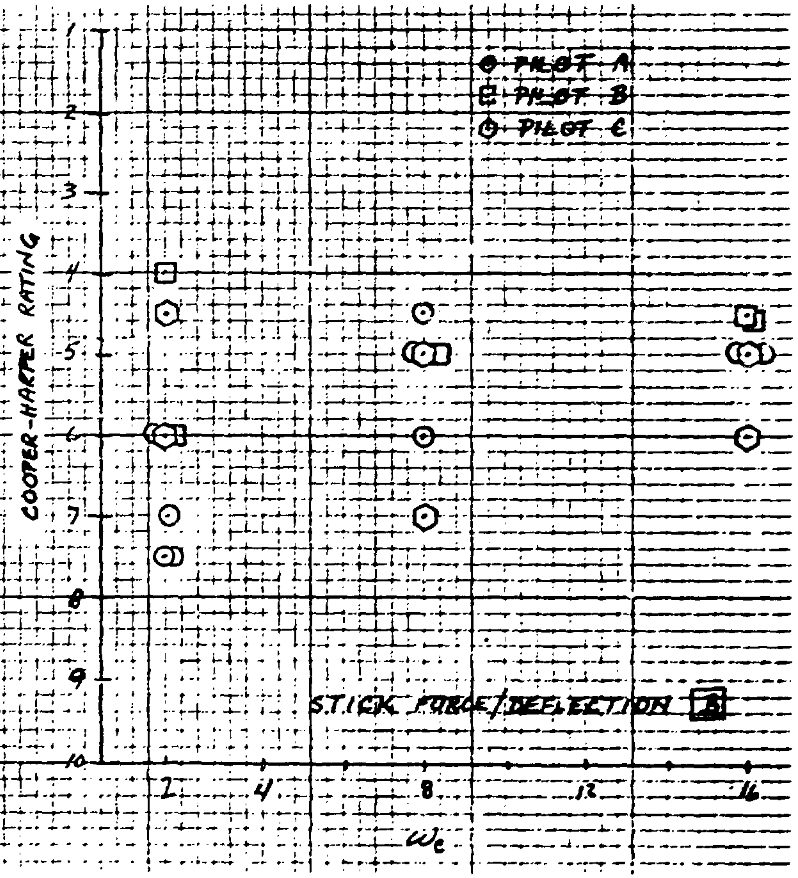


FIGURE 56 Cooper-Harper vs ω_c
Fine Tracking

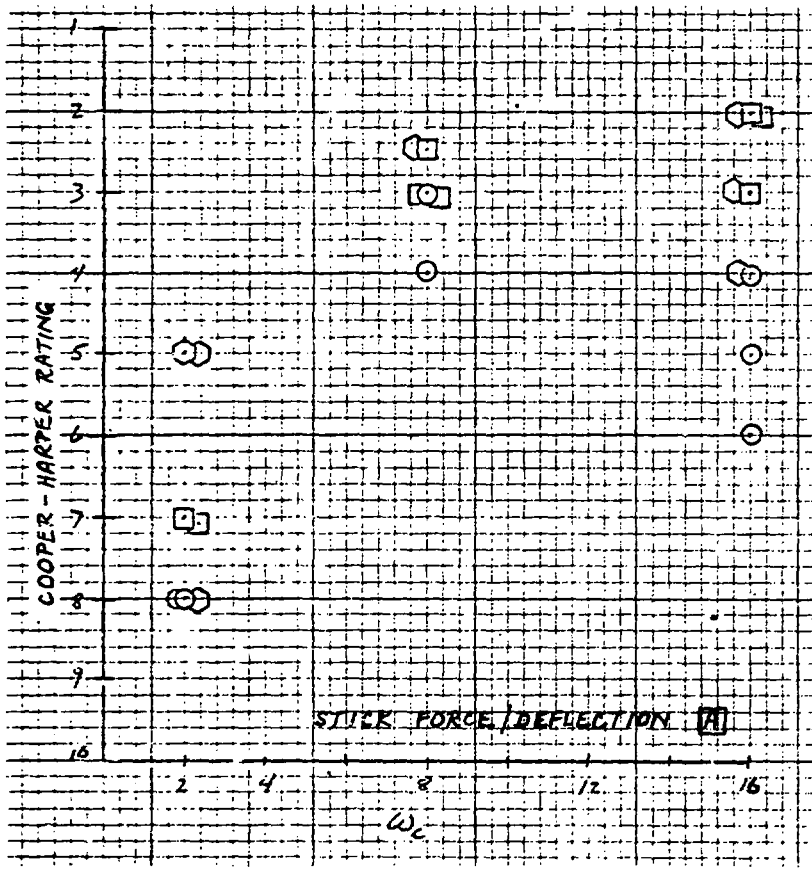


FIGURE 57 Cooper-Harper vs ω_c
Landing

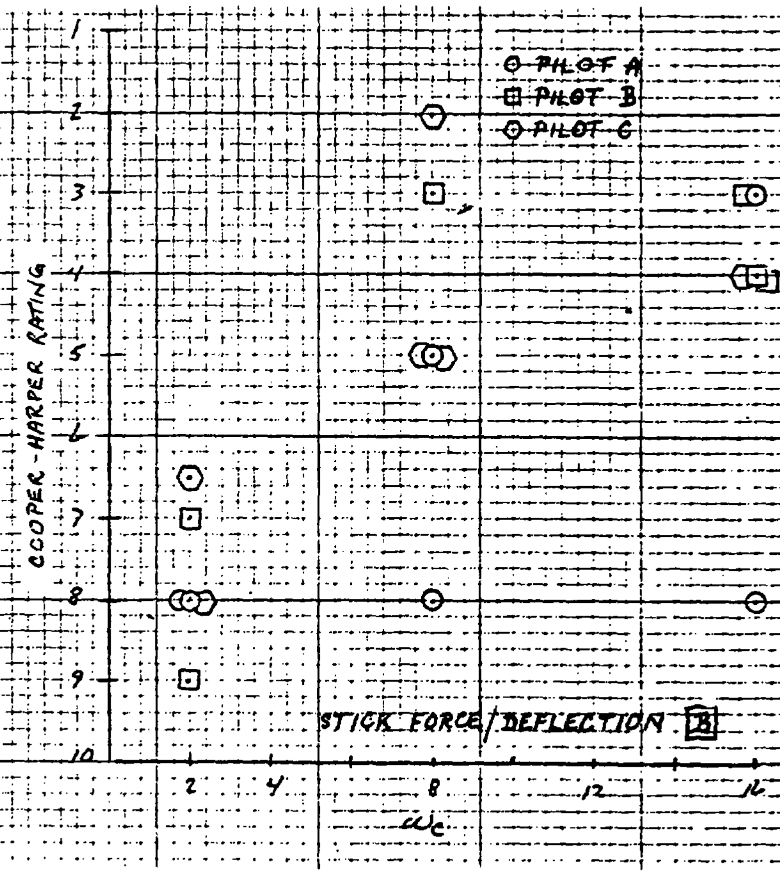


FIGURE 58 Cooper-Harper vs ω_c
Landing

FIGURE 59 PILOT COMMENTS

Gross Acquisition

2A Predictability:

Lateral: Noticeable overshoots. Lateral demands all my concentration. Hard to get in plane.
Pitch: Couldn't stop pipper where desired. Unpredictable. Good "g" onset. Small bobble.
Responsiveness: Not as responsive as I would like. Lateral is too sluggish. Good pitch sensitivity.

8A Predictability:

Lateral: Lateral excursions exceeded pitch. Tend to overshoot in roll. Biggest problem is lateral. Hard to predict. Hard to get in plane.
Pitch: Generally good until last small change. Small tendency to bobble. Some overshoot. Poor "g" predictability.
Responsiveness: Roll a bit sluggish. Good pitch response. Sensitivity good. Not sensitive enough in pitch. Lateral is too sensitive.

16A Predictability:

Lateral: Some problem with plane of motion. Some initial snaking.
Pitch: Not "g" sensitive. Some overshoots. Poor predictability.
Responsiveness: Good initial response. Low roll response. Very quick. Very sensitive but easy to control. Slow lateral response. Good pitch response.

2B Predictability:

Lateral: Poor laterally. Lateral wander. Lateral PIC.
Pitch: Hard to stop precisely. Pitch bobbles. Poor predictability. Easy to overshoot.
Responsiveness: Sensitive in "g". Too sensitive laterally. Not as responsive as desired. Poor initial response to small input. Not responsive enough.

8B Predictability:

Lateral: Lateral axis difficult. Good lateral control. Jerky in roll. Seems to takeoff in azimuth.
Pitch: Low predictability. Some pitch bobble. Good predictability. Good "g" feel. Pitch overshoots.
Responsiveness: Too sensitive in roll. Initial lateral response good. Quick response in pitch. Pitch too sensitive. Good sensitivity.

FIGURE 59 (continued)

16B Predictability:

Lateral: Relatively easy to get in plane. Can get desired performance. Steps in aileron. Overcontrol in roll. Poor predictability.
Pitch: Small overshoots in pitch. Hard to predict 'G'. Sensitive in "g".
Responsiveness: Azimuth too jerky. Not getting pitch rate desired. Sensitivity good.

Fine Tracking

2A Predictability:

Lateral: PIO. Hard to get in plane. A problem in pitch and worse in roll. Wander excessive.
Pitch: Small PIO at times. Always overshooting.
Responsiveness: Not as responsive as would have liked. Sluggish laterally. Pitch lag in wind-up turn.
Other: High workload. Tend to overdrive. Require smooth inputs.

8A Predictability:

Lateral: A little difficult. Tracks pretty well. A little unpredictable. Lateral snaking. Lateral wander.
Pitch: Overcontrol. 3-4 mil bobble. Holds target well. Very small pitch bobble.
Responsiveness: Too sensitive in roll. Low initial response. Pitch sensitive. Low pitch sensitivity.
Other: Overall good. Had to put in lots of control to get pipper to move.

16A Predictability:

Lateral: Lateral wander. Lateral a bit more problem. Easy to make small plane changes.
Pitch: Sensitive but controllable. Bobble in wind-up turn.
Responsiveness: Good pitch response. Pitch sensitivity good. Sluggish lateral response. Good initial response.
Other: A little sensitive - I like the control.

2B Predictability:

Lateral: Large wander. PIO tendency. Too much lateral lag overdrive and lateral overshoot.
Pitch: In wind-up turn, difficult to move pipper, required large inputs. Trouble making small pitch correction.
Responsiveness: Fair initial pitch response--bad initial lateral response. Tended to overdrive in roll. A bit too sensitive. Need more sensitivity.
Other: High workload.

FIGURE 59 (continued)

Note: Comments show no initial response, then overdrive with loss of predictability. This is called both "too sensitive" and "not sensitive" by pilots.

8B Predictability:

Lateral: Overshoots. Overcontrol. 5 mil wander.
Pitch: OK. 5 mil bobble. Many overshoots. Nice. Quite a bit of bobble.
Responsiveness: Jerky in roll--too sensitive. Sensitivity good in pitch. Need more sensitivity in roll. Lateral sensitivity good. Pitch too sensitive, causing overshoot.

16B Predictability:

Lateral: Rigid, causing wander. Steps, not smooth. High compensation. Allows close control.
Pitch: Good. Bobbles. Minimum compensation. Bobble increased with G.
Responsiveness: Good initial pitch response. Lateral too sensitive. Too sensitive in pitch--roll sensitivity OK. Overcontrol in roll. Liked lateral sensitivity. Steps in roll.
Other: Didn't like the feel, but liked the results.

Landing

2A Predictability:

Ballooned. No precise control. Difficult to maintain heading.
Responsiveness: Poor initial response. (No reaction to small inputs). Spongy.
Other: PIO both axes, unresponsive to small inputs then overdrives.

8A Predictability:

Flies excellent if smooth inputs. No tendency to overcontrol or overshoot. Unintentional balloon. Slight unpredictability in pitch.
Responsiveness: Could be more responsive. Initial response to small input poor, then tend to overdrive. Sensitive in flare. Not sensitive enough.
Other: Low frequency bobble. Easy to fly.

16A Predictability:

Easy to fly. Very good pitch and lateral control. Very controllable.
Responsiveness: Lateral OK. Pitch OK. A little sensitive. Roll and pitch responsiveness less than desired.
Other: Flies like I want airplanes to fly.

FIGURE 59 (continued)

2B Predictability:

Poor pitch predictability - PIO tendency. Did not get proper anding attitude. Ballooned. Can't feel aircraft.
Responsiveness: Overcontrol laterally. Overcorrected in pitch. Roll too quick causing overcontrol in bank.
Other: Bad aircraft. Not safe.

8B Predictability:

Small pitch hesitation, then one overshoot. Small bounce in pitch. Low frequency PIO in pitch.
Responsiveness: Too sensitive. Poor sensitivity. Lateral cr rol - OK. Tendency to overrotate.
Other: Have to tone down inputs. Lateral PIO tendency - have to control inputs.

16B Predictability:

Very easily controlled. Pitch bounces. Lateral control - OK. A mild pitch bobble.
Responsiveness: A bit sensitive. Pitch sensitive but OK. Too sensitive for adverse conditions.
Other: Lateral OK.

that the rating assigned to a given configuration varied considerably depending upon which others were also flown on that sortie. It was possible, however, to rank order the configurations flown on a given mission. A preference rating was determined for each configuration by taking its average rank order for the entire test. When these preference ratings are plotted as in Figures 60 through 65, it is possible to identify an overall preference trend for the various tasks.

The validity of this approach is increased by the fact that the Cooper-Harper ratings did not cover the entire spectrum. In other words, pilots were generally agreed that the aircraft needed improvement, but that it was not dangerous. Additionally, each test mission was flown with a different combination of configurations in varying sequences, thereby allowing as complete and unbiased an examination as possible.

Analysis of results will be presented for each task: gross acquisition, fine tracking and landing.

Gross Acquisition.

Gross acquisition showed little prefilter preference in configuration A. Cooper-Harper ratings varied from 4 to 7 for all prefilters. Lateral problems dominated all test configurations. Pilot comments ranged from problems with predicting response with 2 radians/second (lots of lag) and quickness of response at 16 radians/second. The preference ratings showed a slight preference for 16 radians/second. Gross acquisition which involves quickness of response and predictability of motion and response for large sustained inputs showed no significant prefilter preference.

In configuration B, gross acquisition preferences were again insensitive to prefilter changes. Cooper-Harper ratings and comments were similar to those in configuration A except for more comments on sensitivity with the stiffer stick. No significant preference for the gross acquisition task was evident at any combination of force/deflection characteristics or prefilter corner frequencies in the six point test matrix.

Fine Tracking.

In configuration A, the 2 radian/second test point (increased lag) clearly degraded fine tracking performance. Pilots complained of "sluggish" response and high workloads. Cooper-Harper ratings, preference ratings, and CALCOMP data show poor results at 2 radians/second. At all test points, the lateral control problem was more difficult than pitch control. The Cooper-Harper ratings and preference scale show some pilot preference for 8 radians/second over 16 radians/second even though objective results from CALCOMP indicated better performance at 16 radians/second. Pilot comments indicated that the small amount of lag at 8 radians/second decreased pitch bobble on the target and resulting pilot workload.

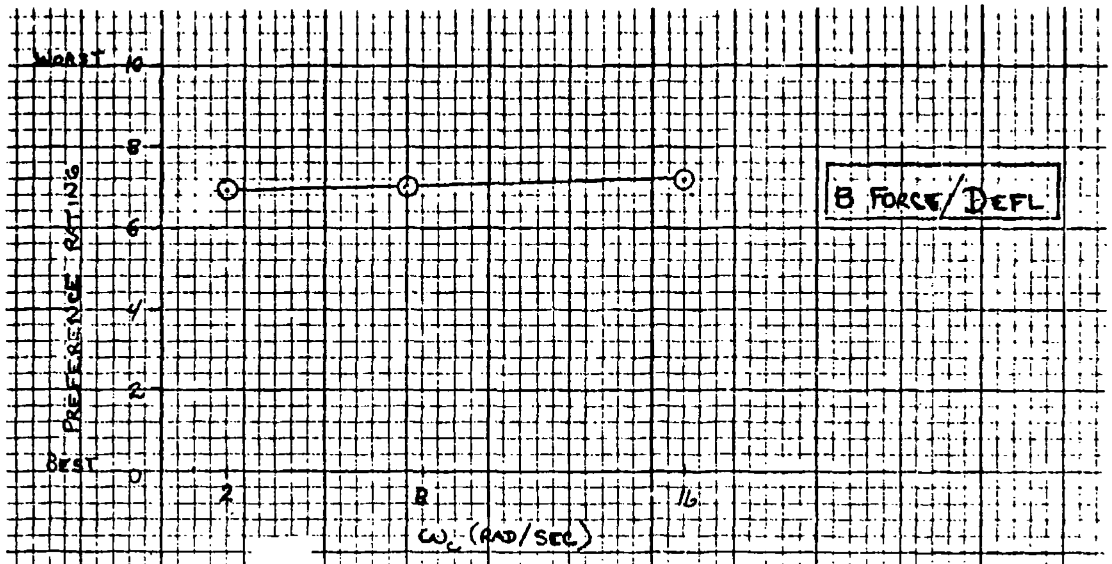


FIGURE 60 Preference Rating vs ω_c
Gross Acquisition

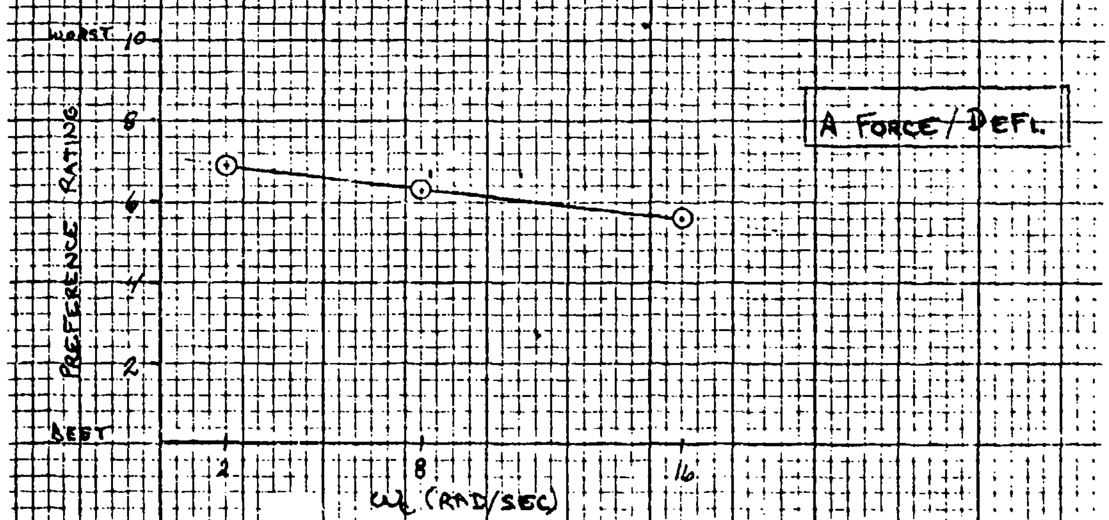


FIGURE 61 Preference Rating vs ω_c
Gross Acquisition

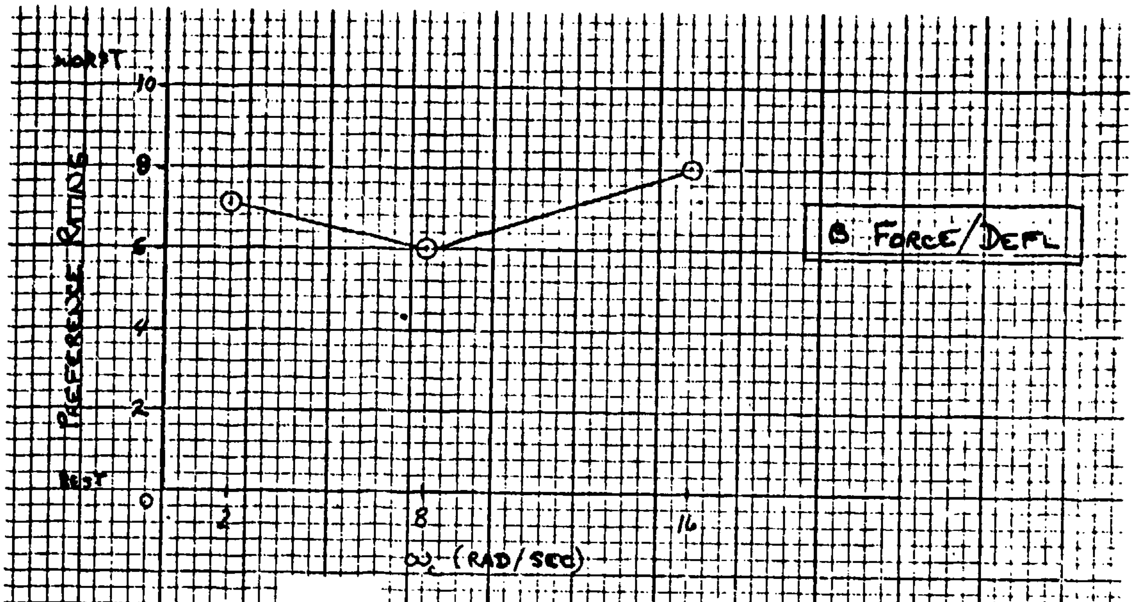


FIGURE 62 Preference Rating vs ω_c
Fine Tracking

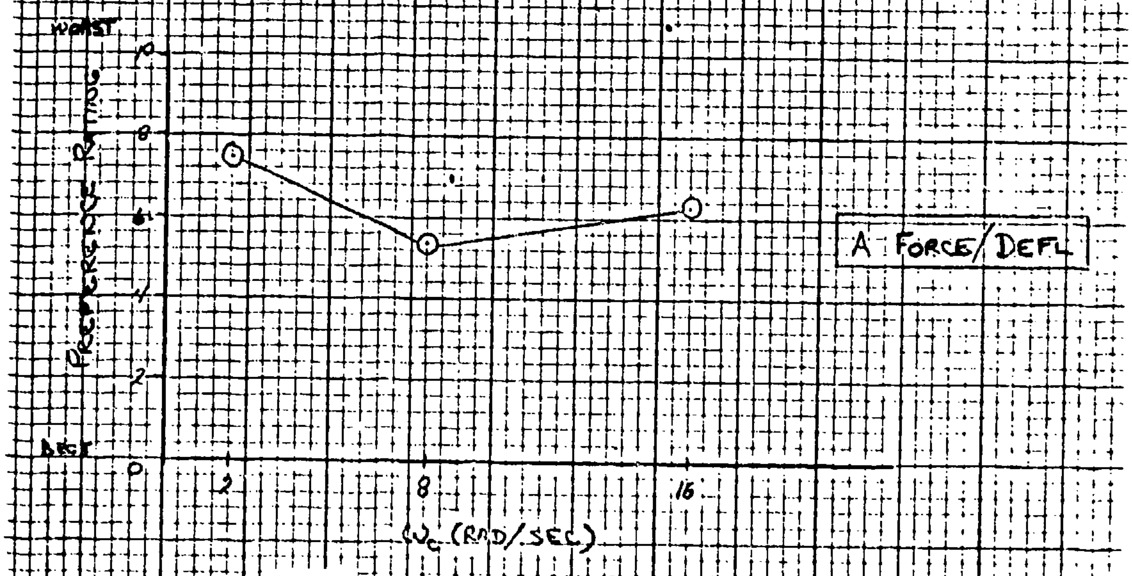


FIGURE 63 Preference Rating vs ω_c
Fine Tracking

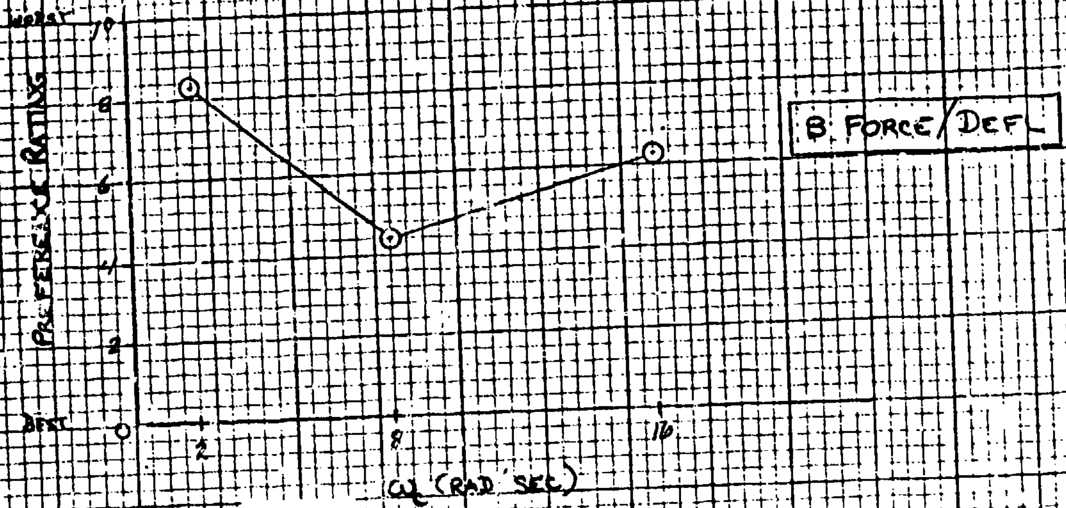


FIGURE 64 Preference Rating vs ω_c
Landing

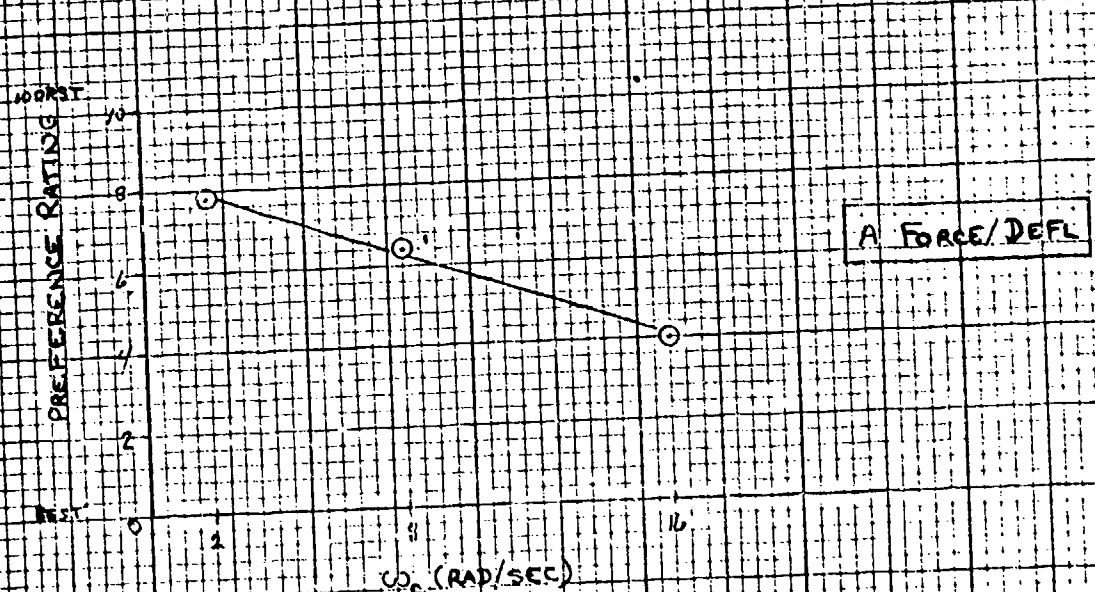


FIGURE 65 Preference Rating vs ω_c
Landing

In configuration B the 2 radian/second prefilter produced widely varying results. Cooper-Harper ratings varied from 4 to 7. Pilot comments varied from praise of the results to complaints. A high workload when actually achieving reasonable tracking results was evident. Actual performance as measured by CALCOMP also varied widely from some of the best tracking in configuration B to some of the worst. With the high amount of lag, the configuration was apparently sensitive to changes in pilot inputs, whether due to atmospheric conditions, pilot fatigue, or some change in individual gain or time constant. It is obvious that although the average performance and ratings at 2 radians/second compares well to other prefilter test points in configuration B, the extreme variability of pilot evaluations makes this high sensitivity/high lag combination less desirable.

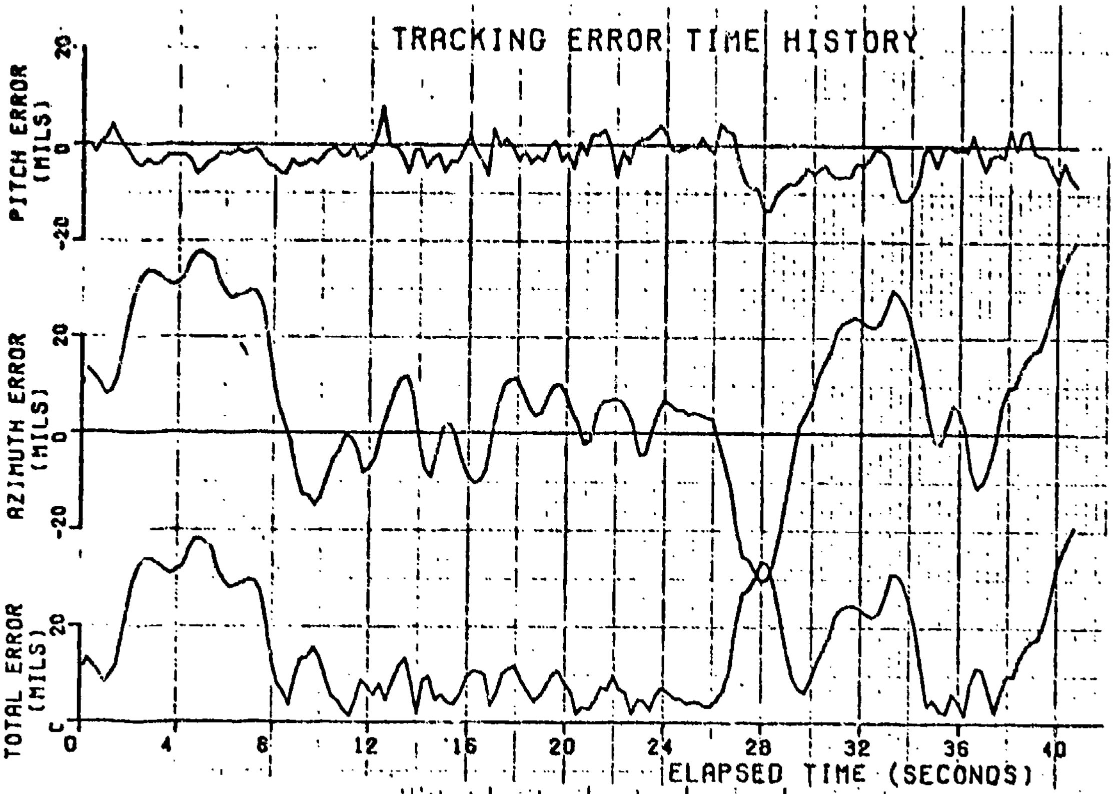
Objective CALCOMP data indicates that 16 radians/second in configuration B was best. Preference ratings showed a preference for 8 radians/second. Cooper-Harper ratings indicate a slight preference at 16 radians/second. As with configuration A pilots liked the responsiveness of 16 radians/second but also liked the decreased pitch bobble and decreased pilot workload provided with 8 radians/second.

Overall, 8 radians/second was slightly preferred by the pilots for fine tracking in both configuration A and configuration B even though 16 radians/second provided better performance.

In all of the air-to-air tasks, azimuth errors proved to be the largest problem (see Figure 66). Typically, pilots complained of an inability to get in the plane of motion of the target resulting in a large amplitude, low frequency azimuth wander (Figure 66). Pilots sometimes felt that the lateral tracking problem was so great that it prohibited a fair evaluation of the pitch response, especially in lazy eight maneuvers. Occasionally, configurations with rather poor pitch characteristics were given relatively good ratings if the pilot felt that the azimuth problem was reduced. This is particularly apparent in configuration 2B, where the sensitivity of the B stick force/deflection configuration allowed the pilot to "manhandle" the lateral axis to an improved, but still poor, azimuth solution.

The magnitude of this problem is evident in the pilot ratings for the air-to-air tasks. Even the previously determined optimum configuration (reference 3), 16A, received Cooper-Harper ratings in the 4 to 6, "deficiencies warrant improvement", range. Tracking performance (Figure 67) confirms the imprecise tracking in all configurations despite the high level of experience of the test team pilots (Figure 68). Pilot ratings and performance data suggest that the azimuth error problem may have masked more subtle handling qualities variations with changes in the prefilter.

Analysis of magnetic tape data showed that during steady turns, the NT-33A maintained a residual sideslip angle (approximately one degree or 17 mils). This is what prevented the pilots from maintaining the pipper on the target in azimuth while staying in the target's plane. Therefore, it is recommended that the residual sideslip in steady turns be eliminated prior to further handling qualities during tracking testing in the NT-33A.



Pilot: Tilden

Force/Defl.: B

Prefilter: 2 rad/sec

Target maneuver: Lazy Eight

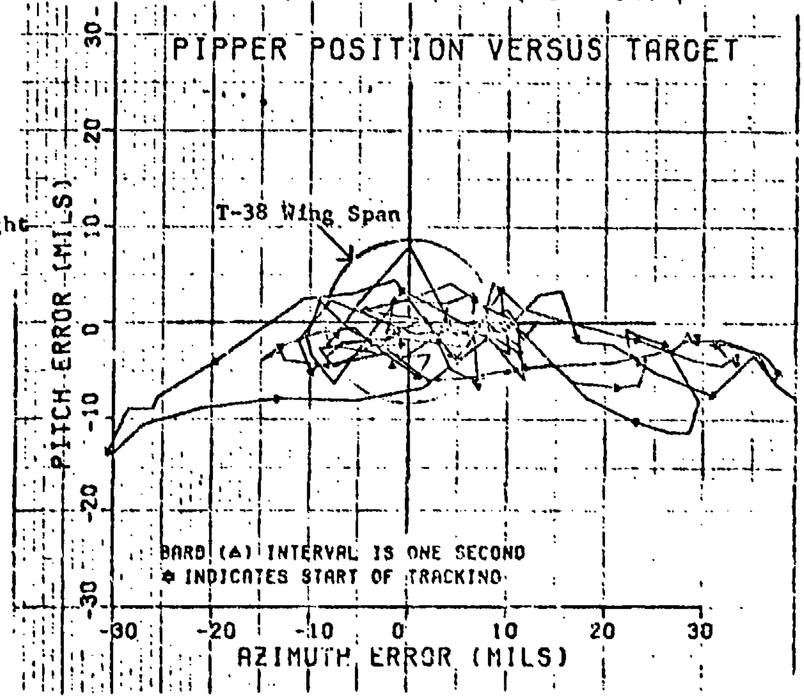


FIGURE 56 Tracking Errors in Lazy Eight Maneuvers

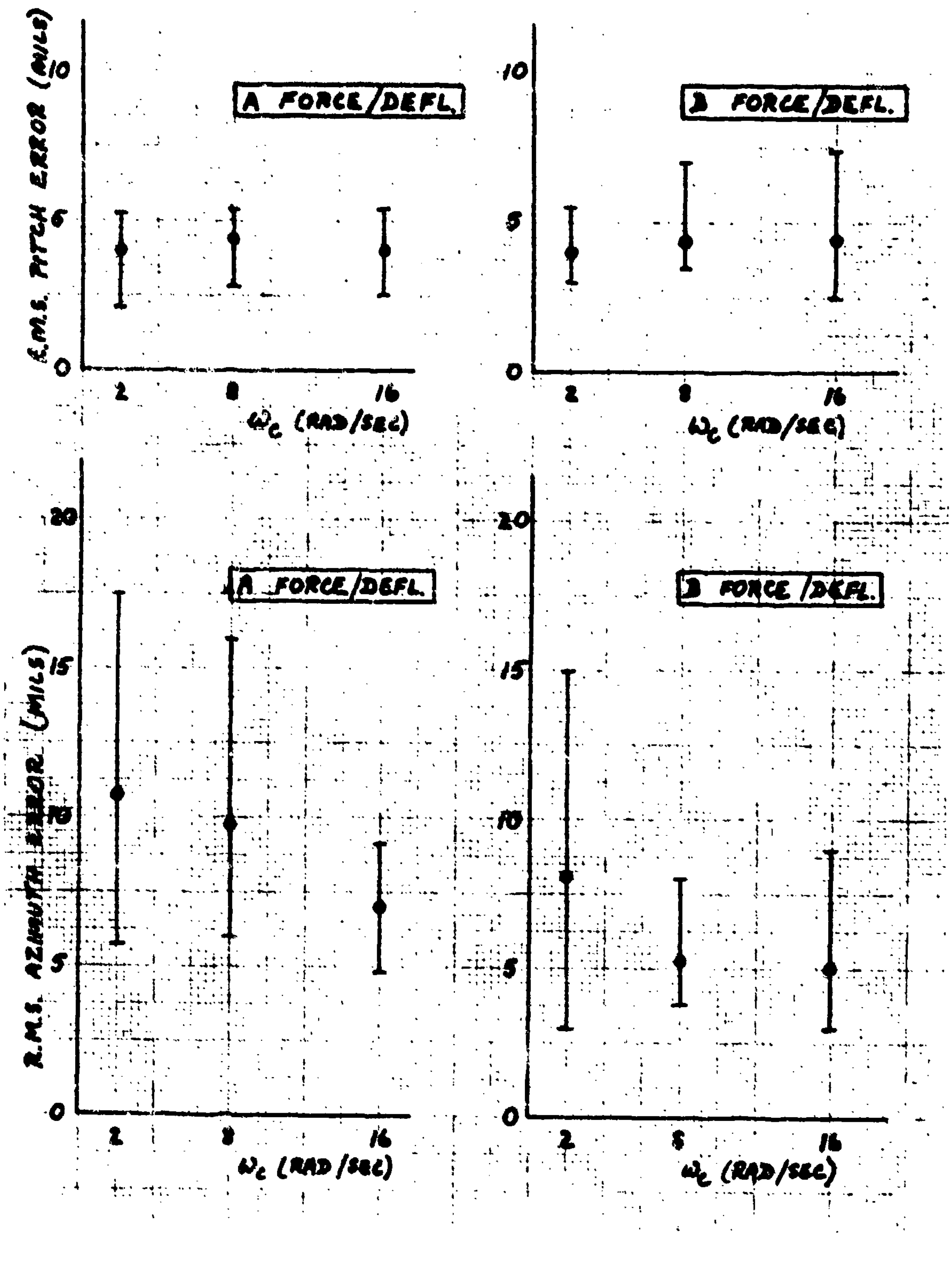
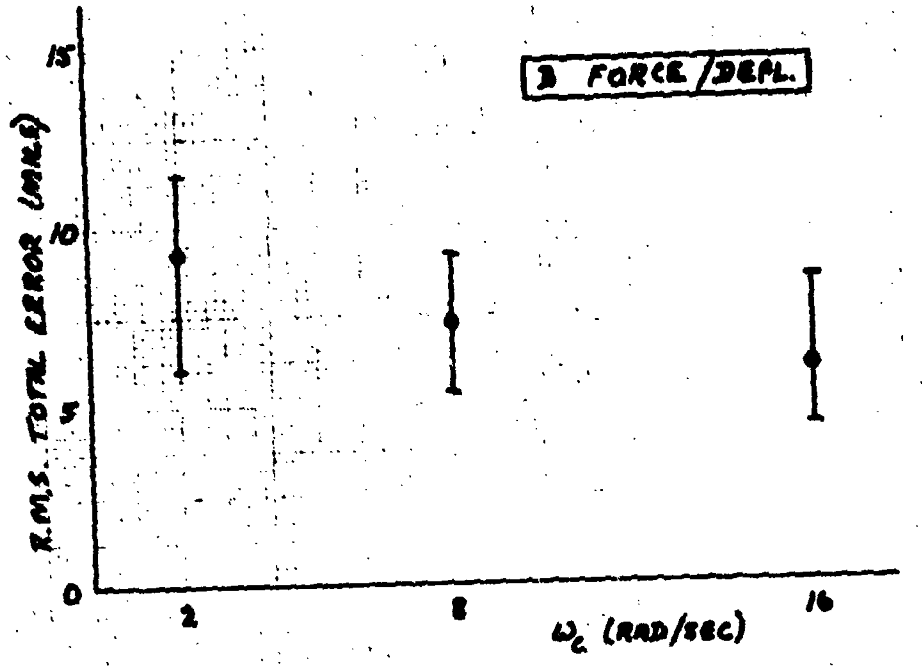


FIGURE 67 Tracking Errors in Constant α and Wind-Up-Turn Maneuvers



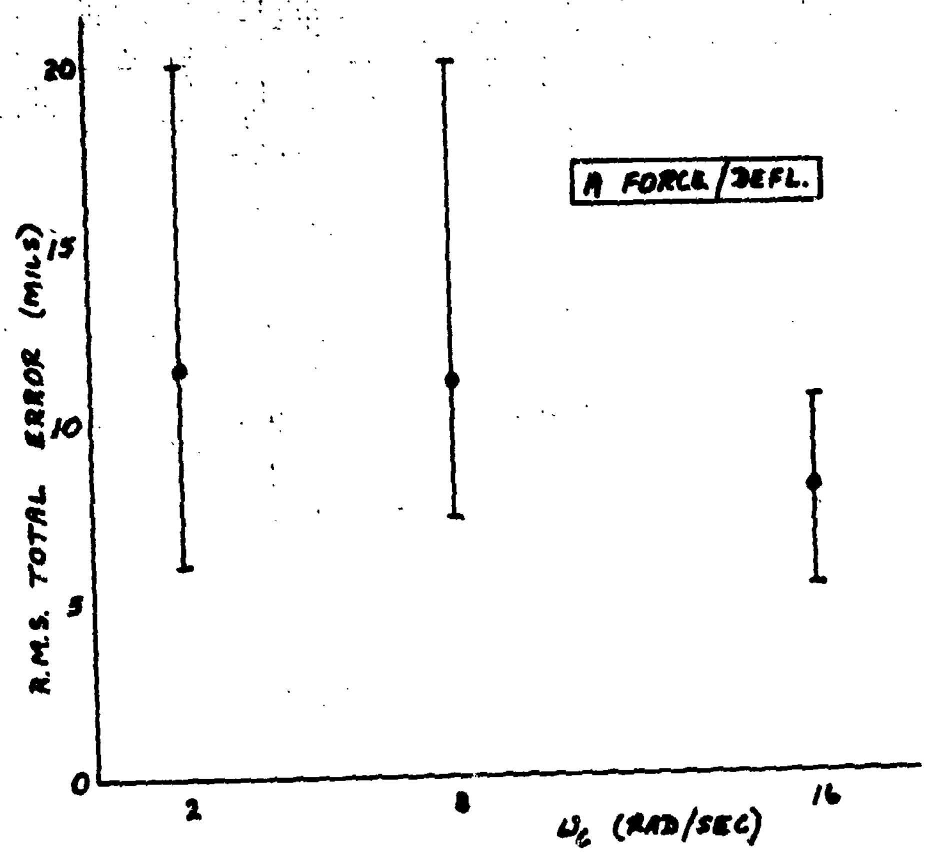


FIGURE 67 (cont) Tracking Errors in Constant α and Wind-Up-Turn Maneuvers

FIGURE 68 PILOT BACKGROUND INFORMATION

PILOT A:

Capt G. V. Lewis
F-4(C/D/E)--950 hours, SEA combat tour
Mission: Air-to-air and air-to-ground
T-38--200 hours
Mission: Photo/Safety Chase

PILOT B:

Capt T.V. Tilden
F-4(C/D/E)--2300 hours (700 hours IP), SEA combat tour
Mission: Air-to-air and air-to-ground
Previous Navigator, 2000 hours C-130E, Light Aircraft

PILOT C:

Capt M. Shmul
Fuga-Magister--900 hours (650 hours IP)
Mirage, KFIR--2000 hours, Middle East Combat Experience since 1966
Mission: Air-to-air and air-to-ground
Executive jet, light transport, light aircraft--300 hours

Landing.

The landing task showed the clearest contrast in pilot preference with changes in prefilter.

In configuration A, 16 radians/second was clearly preferred. Note that 8 radian/second has been used in all previous tests in the landing configuration. The preference ratings indicated a strong preference for 16 radians/second. Comments indicated that as lag increased the aircraft was not responsive enough initially, then the pilot would overdrive his input resulting in poor predictability.

With configuration B, the more sensitive deflection characteristics, a slight shift in preference was evident. Configuration B was less desirable than A. At 2 radians/second, characteristics of overdriving and unpredictability were again evident but the sensitivity made this test combination close to uncontrollable. However, 8 radians/second was a clear preference on the preference ratings and compared well to 16 radians/second on the Cooper-Harper ratings. Although 8 radians/second was preferred, no change in prefilter within the range tested would improve pilot evaluations of configuration B to match configuration A. The additional lag at 8 radians/second had slightly improved the characteristics of configuration B but not as much as just flying with configuration A.

Future Tests.

Generally, pilots preferred more lateral sensitivity and less pitch sensitivity for air-to-air tasks. This may have been due to the lateral characteristics of the NT-33A and/or the physical characteristics of sidestick controlled aircraft. It is recommended that future tests of sidestick controller characteristics evaluate variations in control harmony between the pitch and roll axis.

CONTROL HARMONY

Although it was not part of the original test objectives, a very limited investigation of control harmony was conducted during the test. On five of the nineteen test sorties, one evaluation of a stiff, sensitive lateral and nominal pitch sensitivity stick was conducted. This configuration was:

Axis	Force	Deflection	Prefilter (ω_c)
Pitch	.167 g/lb	.7 deg/lb	2.5 rad/sec
Lateral	7 deg/sec/lb	.3 deg/lb	16 rad/sec

Air-to-Air Tasks.

Three evaluations, one by each project pilot, were conducted for gross acquisition and fine tracking. During these flights, all three pilots considered it to be the best configuration for both gross acquisition and fine tracking, as compared to the other configurations seen on that flight (2B and 8A in all three cases).

From limited HQDT Calcomp plots, the average R.M.S. errors for fine tracking in constant g and wind-up turns are:

Pitch	-	3.62 mils
Azimuth	-	9.04 mils
Total	-	9.82 mils

A comparison of these errors to those shown in Figure 67 do not indicate a marked improvement. However, when examining the lazy-eight maneuver, it is found that the performance was dramatically improved. Figure 69 shows a Calcomp plot for the best tracking during lazy-eights for any of the original test configurations. Figure 70 shows the only lazy-eight recorded on film with the mixed harmony configuration.

Pilot comments indicate that this was the best performing configuration. However, two of the three pilots complained about the control harmony and especially about the jerkiness in roll.

Landing.

Two landings were made in this configuration. In the landing task, this configuration was not optimum. While no comments were made concerning control harmony, it was mentioned that there was not enough pitch responsiveness, while the lateral sensitivity was okay. Cooper-Harper ratings were 5 and 5.5, which are well below the ratings given for configurations 16A and 8B.

CONCLUSIONS AND RECOMMENDATIONS

The specific objectives of the NT-33A test were to determine the preferred first order prefilter for a given force/deflection configuration and to determine the variation of prefilter preference with force/deflection changes. Overall analysis of the results show that there was an identifiable preference for a prefilter for two out of the three tasks evaluated, and that this preference changed when the stick force/deflection was changed.

More specifically, in the gross acquisition task, pilots indicated little preference for one prefilter over another in both configurations A and B.

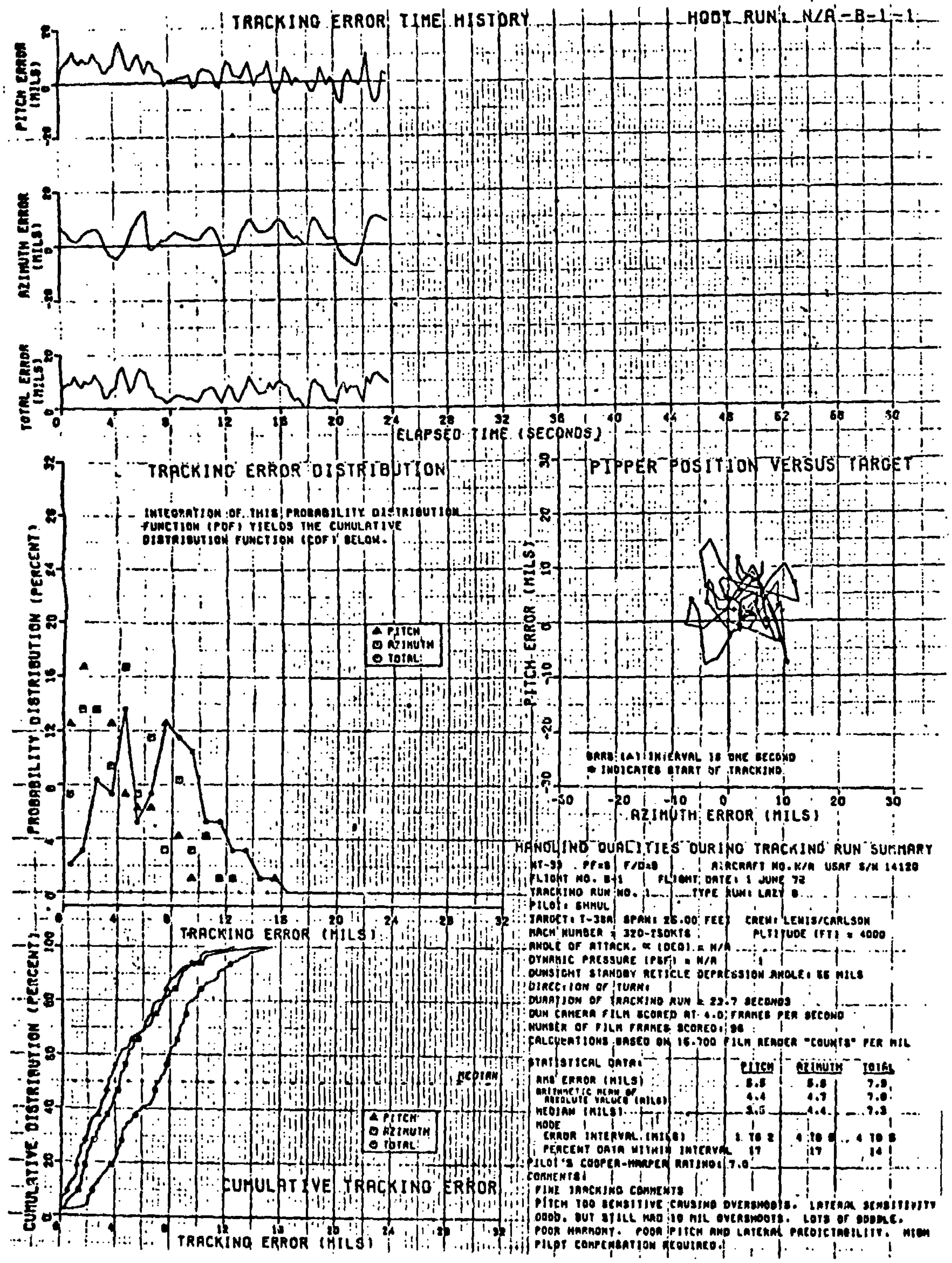


FIGURE 69 Tracking Results

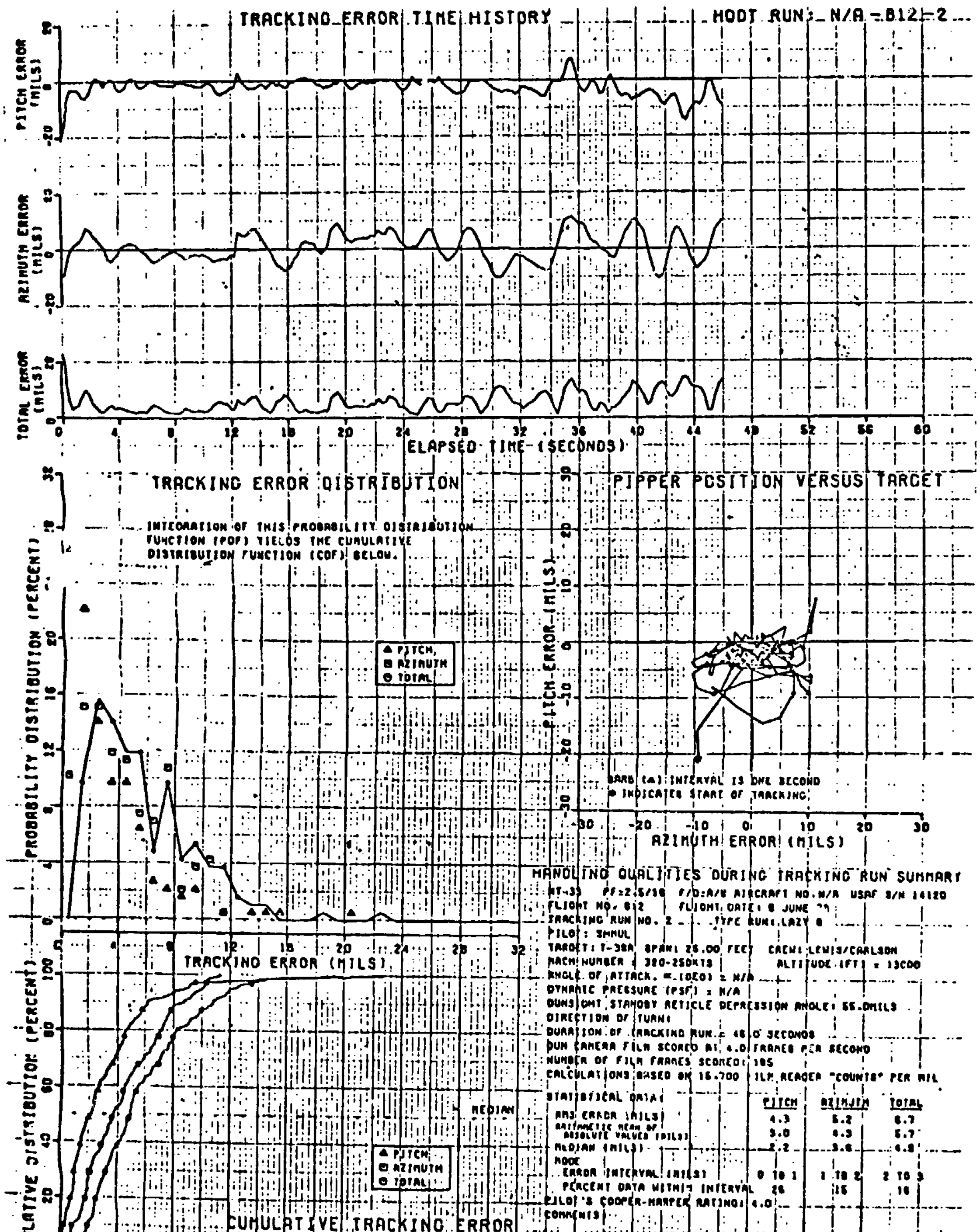


FIGURE 70 Tracking Results

During fine tracking maneuvers, the greatest difference in preference was a degradation with the 2 radians/second prefilter. Although the differences between 8 and 16 radians/second prefilters were smaller, the pilots did prefer the former. Performance was, however, slightly better with 16 radians/second in both configurations.

The landing task provided the clearest contrast in pilot preference with prefilter changes. In configuration A there was a strong preference for 16 radians/second while in configuration B the 8 radians/second prefilter was the pilot's choice. In both cases, the 2 radians/second prefilter was considered to be the least desirable. It is noteworthy that in all cases configuration A was considered superior to configuration B.

In all air to air tracking tasks, azimuth problems were significant. Pilots had a great deal of difficulty in staying in the plane of the target which resulted in large amplitude, low frequency azimuth wander. The NT-33A maintained a residual sideslip angle which prevented the pilots from keeping the pipper on the target in azimuth.

NT-33 RESIDUAL SIDESLIP IN STEADY TURNS SHOULD BE ELIMINATED PRIOR TO FURTHER HANDLING QUALITIES DURING TRACKING TESTING.

Pilot comments indicated that control harmony was not optimized. Generally, more lateral sensitivity and less pitch sensitivity was preferred.

FUTURE TESTS OF SIDESTICK CONTROLLED AIRCRAFT SHOULD INVESTIGATE VARIATIONS IN CONTROL HARMONY BETWEEN PITCH AND ROLL AXIS.

APPENDIX E

TECHNICAL RESULTS AND DISCUSSION FROM USAF TEST PILOT SCHOOL LETTER REPORT - 6 December 1978 "Limited Flight Evaluation of the Effect of Modal Dynamics Variations on the Handling Qualities of Sidestick Controlled Aircraft" by W.W. Copeland, LCDR, USN; J.R. Anderson, Captain, USAF; R.T. Banholzer, Captain, USAF; M. Dvir, Major, IAF; C.R. Jones, Captain, USAF and L.R. Perlee, Captain, USAF.

ABSTRACT

A limited investigation was conducted to determine the effect of modal dynamic variations on the handling qualities of sidestick controlled aircraft. The test aircraft, AFFDL's variable stability NT-33A, was configured with one of five sets of aircraft dynamics, one sidestick deflection gradient, and one of two sets of stick force response characteristics, and was then evaluated through a well defined series of air-to-air tracking tasks. Pilot comments, tracking performance, and Cooper-Harper ratings were analyzed for all configurations.

The test results for all tracking tasks show a pilot preference for the baseline (medium) short-period frequency dynamics given a heavy sidestick force response, and the low short-period frequency dynamics given a light sidestick force response. Pilot preference for the baseline (medium) roll mode time constant was independent of sidestick force response characteristics. Given a set of aircraft dynamics, pilot preference for the sidestick force response characteristic was a function of the dynamics and the air-to-air tracking maneuver.

A total of 45 calibration, data, target support, and practice sorties totalling 63.0 hours were flown at the Air Force Flight Test Center, Edwards AFB, California from 27 October 1978 to 27 November 1978.

TEST METHOD/CONDITIONS

Test Configurations.

The air to air dynamics simulated by the NT-33A are shown in Table IX. The chosen dynamics represent the Level 1 range of longitudinal short period and roll mode time constant parameters as defined by MIL-F-8785B[21]. The sidestick deflection gradients were fixed at 1.19 lb/degree in the longitudinal axis and 0.95 lb/degree in the lateral axis. The sidestick force response characteristics are shown in Figure 71. A test configuration consists of a set of dynamics and a set of sidestick force response characteristics. The test configurations are shown in Figure 72. A control system prefilter corner frequency of 16 radians/sec and $N_{\delta a}/L_{\delta a}$ ratio of 0.016 was used for all test points. The selected corner frequency is the least limiting to pilot inputs of the values used in previous efforts. Sidestick controller armrest position was determined by individual pilot preference and was held constant throughout the evaluation.

Test Point Selection.

Test points were selected to allow equal pilot exposure to each configuration. Points were sequenced to minimize biases due to the pilot learning curve effect and due to contrast between configurations. Priority was placed on studying effects of short period variations over roll mode time constant variations. Within these considerations, points were presented to the pilots in a scrambled order, and project pilots were not made aware of the configurations being flown. The NT-33A safety pilot was informed of the required configurations before each flight.

Mission Description.

Each mission consisted of the following phases:

a. Mission briefing

b. Take-off and join up

c. Air-to-air tracking tasks

d. Landing

e. Mission debriefing

Mission Briefing.

Each mission began with a briefing conducted by project personnel one hour and thirty minutes prior to the planned take-off time. Minimum attendance at this briefing was the NT-33A pilot and safety pilot, the T-38A pilot, and the project engineer flying in the rear seat of the T-38A. At the briefing, project personnel insured that mission data cards were complete and that all necessary instrumentation was functional.

TABLE IX. AIR-TO-AIR DYNAMICS SETS

PARAMETER	DYNAMICS SETS				
	High ω_{SP} (A)	Low ω_{SP} (B)	Baseline (C)	Short τ_R (D)	Long τ_R (E)
ω_{SP} (radians/sec)	10	3.0	5.5	5.5	5.5
ζ_{SP}	0.65	→	→	→	→
N_z/α (g/radians)	29	→	→	→	→
τ_R (sec)	0.35	0.35	0.35	0.20	0.95
ω_{DR} (radians/sec)	4.0	→	→	→	→
ζ_{DR}	0.35	→	→	→	→
ϕ/β	2.0	→	→	→	→
τ_S (sec)	∞	→	→	→	→

NOTE: V[illegible]ues [illegible]a are nominal values

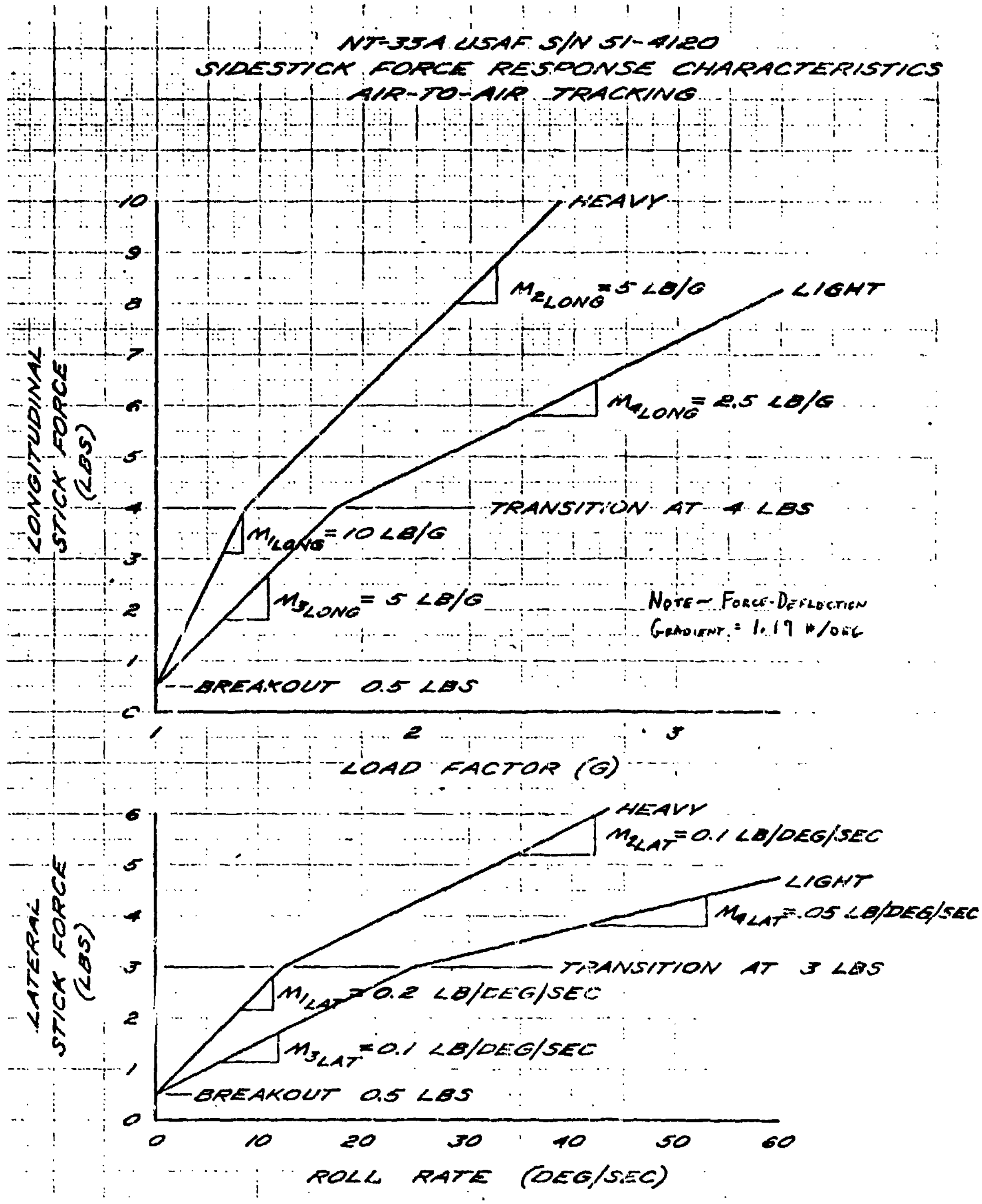


FIGURE 71 Sidestick Force Response Characteristics Air-To-Air Tracking

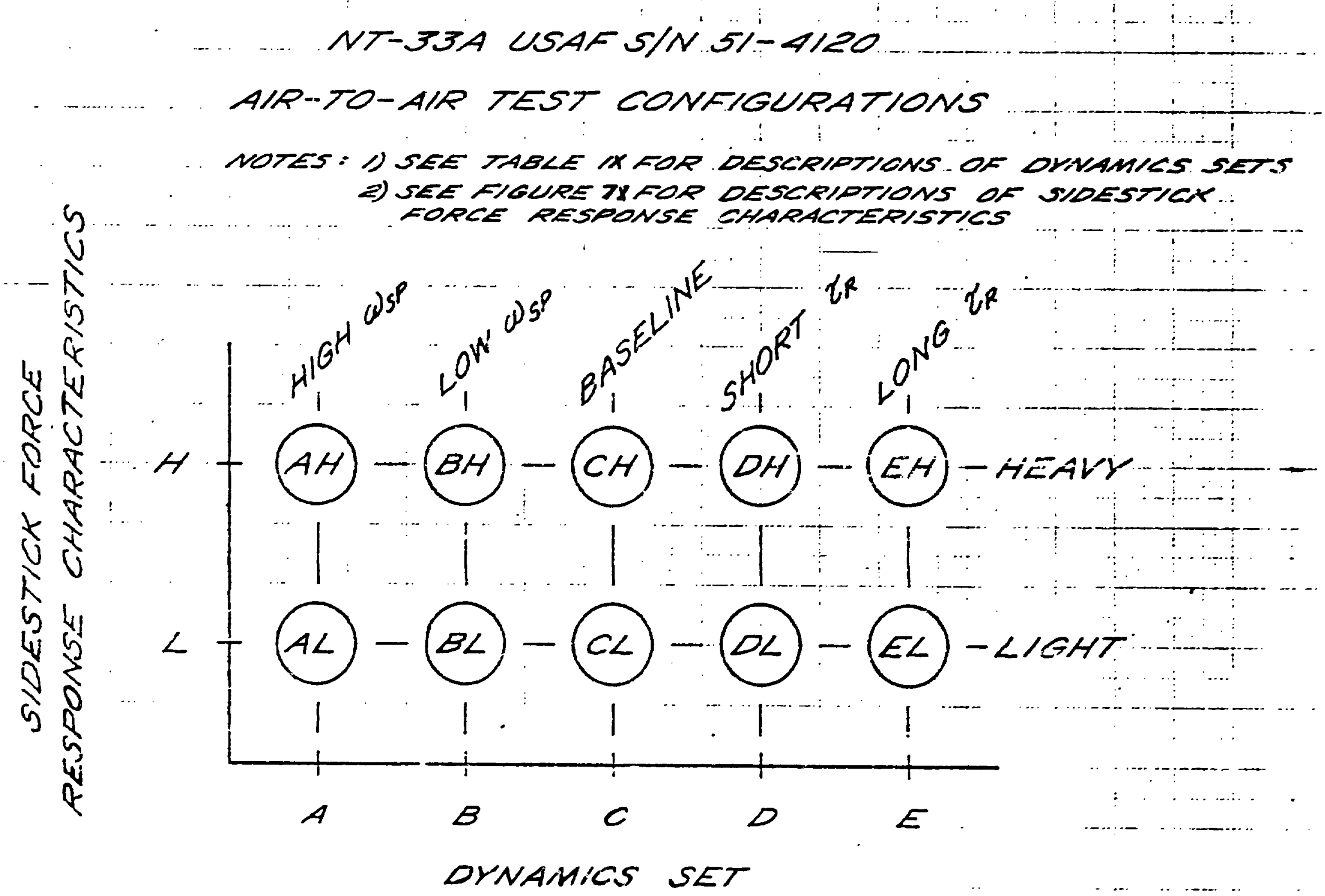


FIGURE 72. AIR-TO-AIR TEST CONFIGURATIONS

Take-off and Join-Up.

After engine start, the NT-33A pilot performed a control sweep and recorded it on magnetic tape. AFFTC Manual 55-2 formation taxi, "last chance", takeoff, and join up procedures were used. Following join up, The T-38A pilot took the lead and proceeded to 13,000 feet MSL in the test area. During the climb, the NT-33A pilot maintained route formation using basic T-33 dynamics and sidestick controller characteristics.

Air-to-Air Tasks.

The air-to-air tasks were performed as described below. Each maneuver was performed twice, once in each direction. Both aircraft returned to base at the completion of the air-to-air testing.

Mission Debriefing.

The NT-33A pilot handcarried the magnetic tape, audio tape and gun camera magazines to the debriefing. Each mission ended with a debriefing including the NT-33A pilot and safety pilot, the T-38A pilot, and the project engineer.

Air-to-Air Tasks.

The air-to-air tasks began with the NT-33A trimmed for level flight at 13,000 feet pressure altitude and 300 KIAS. The NT-33A was not retrimmed during the tasks. The tasks were performed without using the rudder (i.e., feet on the floor) and with a fixed gunsight depression of 55 mils.

Gross acquisition task. The NT-33A pilot aggressively placed the pipper on the T-38A tailpipe junction. When the pipper was held within five mils of the tailpipe junction, fine tracking started. This task was evaluated using maneuver #1 below.

Maneuver #1. The NT-33A pilot established 1500 feet separation as the T-38A pilot initiated a 2g, 300 KIAS, level turn. The NT-33A pilot called "tracking" when fine tracking began. After 10 seconds of tracking, the T-38A pilot performed an unloaded level reversal, using half stick deflection, to a 2g, 300 KIAS, level turn in the opposite direction. The NT-33A pilot waited until the T-38A crossed the canopy bow prior to maneuvering, called "hack", and aggressively maneuvered to reacquire the T-38A and start fine tracking. The NT-33A pilot called "tracking" when gross acquisition ended and fine tracking commenced. After 15 seconds of fine tracking, an additional reversal sequence was accomplished. The T-38A pilot called "knock it off" 15 seconds after the last "tracking" call. Both aircraft were then rolled wings level.

Fine tracking task. The NT-33A pilot precisely and assiduously kept the pipper centered on the T-38A tailpipe junction. This task was evaluated using Maneuvers #2 and #3 below.

Maneuver #2. The NT-33A pilot established 1500 feet separation from the T-38A with both aircraft in a 10 degree bank, 300 KIAS, level turn. When the NT-33A pilot called "tracking", the T-38A pilot initiated a wind-up turn from 1g to 3.0g at 0.2g per second at a constant 300 KIAS. Ten seconds after the T-38A reached 3.0g, the T-38A pilot called "knock it off". Both aircraft were then rolled wings level. The NT-33A pilot then paused to record additional comments prior to beginning maneuver #3.

Maneuver #3. After the NT-33A pilot established 1500 feet separation, the T-38A pilot initiated a 2g, 300 KIAS, level turn. The NT-33A pilot called "tracking" when fine tracking began. After 10 seconds of level tracking, the T-38A pilot reversed the turn at 10 degrees per second of roll, maintaining 2g, and returned to a 2g, level turn. The NT-33A pilot continued fine tracking throughout the reversal and level turn. Both aircraft pilots accepted the resulting airspeed loss during the reversal and did not attempt to maintain 300 KIAS throughout the maneuver. After 10 seconds of level turn, the T-38A pilot called "knock it off". After the "knock it off" call, both aircraft were rolled wings level.

Following the completion of each task, the NT-33A pilot recorded additional comments and completed the inflight comment card. After both tasks were completed, open loop records were taken, and then the NT-33A was configured for the next test point. The above sequence was repeated for each air-to-air test point. During the maneuvers, the NT-33A pilot attempted to maintain 1500 feet separation, but at no time allowed the separation to decrease to less than 1000 feet. The NT-33A magnetic tape system, audio recorder, and gun camera was run during each task.

TEST RESULTS

Pilot comments and Cooper-Harper ratings were provided for each maneuver and test configuration flown. Condensed pilot comments are contained in Figure 73, and a summary of Cooper-Harper ratings, compiled by pilot, flight number, maneuver, dynamics set and sidestick force response characteristic, is provided in Table X. On several flights, overall Cooper-Harper ratings of a test configuration were given and are also included.

Since the range of Cooper-Harper ratings given by each pilot differed noticeably, a ranking scheme was used to aid in analysis. For each of the three maneuvers, individual pilot Cooper-Harper ratings were rank ordered and assigned an integer ranking with the integer 1 corresponding to the pilot's best Cooper-Harper rating. In the case of ties, the midrank method was used. The rankings for a given test configuration were then averaged

FIGURE 73 CONDENSED PILOT COMMENTS

NOTE: See Figure 72 for explanation of test configuration codes.

Configuration AH:

Maneuver 1: non-oscillatory in both axes; control harmony satisfactory with longitudinal force slightly higher than lateral force. C.H. 4,4,5

Maneuver 2: longitudinal and lateral force too high; slight pitch bobble which decreased under increasing g. C.H. 4,4,6

Maneuver 3: lateral control was imprecise under g load while rolling; stick forces are too high in both axes. C.H. 4,5,5

Configuration AL:

Maneuver 1: too fast of a longitudinal response; too oscillatory; imprecise; longitudinal axis too sensitive. C.H. 4,5,6

Maneuver 2: longitudinal response is too fast, oscillatory, imprecise; above two g's less oscillatory; control harmony poor-too sensitive longitudinally. C.H. 5,5,4

Maneuver 3: same comments as Maneuver #2. C.H. 4,3,5.5

Configuration BH:

Maneuver 1: longitudinal stick forces are too heavy; control harmony is good; slow response in both axes; more precise longitudinally than laterally. C.H. 3,6,5

Maneuver 2: longitudinal axis the best; high longitudinal stick force high pilot workload. C.H. 4,4,6

Maneuver 3: sluggish response longitudinally, however it is precise and non-oscillatory; lateral axis is imprecise; moderate lateral pilot compensation; control harmony unsatisfactory. C.H. 4,4,4.5

Configuration BL:

Maneuver 1: longitudinal axis very good with a slightly slow initial response; imprecise lateral axis. C.H. 3,3,5

Maneuver 2: excellent longitudinal response; slight problem making small corrections laterally. C.H. 2,2,4

Maneuver 3: excellent longitudinal response; slight lateral imprecision during rolling portion of cine-track maneuver. C.H. 2,2,5

Configuration CH:

Significant discrepancy exists; two of the four evaluations were considered good, two were poor; within each evaluation comments and ratings were in agreement; during the poor evaluations, unexplainable sideslip oscillations were present for the same open loop dynamics - reason(s) remain unknown.

FIGURE 73 (continued)

Configuration CL:

Maneuver 1: initial longitudinal response is good; precise, but some pitch bobble; lateral overshoot when trying to stop pipper on target. This caused the discrepancy in C.H. ratings; two pilots talking about stopping the pipper, the other on the dynamic motion. C.H. 3,3,6*

Maneuver2: high frequency small oscillation in the longitudinal axis; imprecise laterally due to low frequency oscillation; minimum pilot compensation necessary; good aircraft. C.H. 3.3,6*

Maneuver 3: some longitudinal characteristics; good pitch control; lateral axis more imprecise, tendency for a slight lateral PIO; still a good configuration. C.H. 3,4,6*

*The identical difficulties encountered with configuration (CH) were experienced by Pilot C during one evaluation; the comments noted above for each maneuver were those for Pilots B and D.

Configuration DH:

Maneuver 1: good gross acquisition in both axes; very slight longitudinal oscillation. C.H. 2,4

Maneuver 2: longitudinal force slightly higher than lateral force; lateral axis more sensitive than longitudinal axis. C.H. 2,4

Maneuver 3: good longitudinally; oscillatory laterally; tend to overcontrol laterally; control harmony unsatisfactory - lateral force too high. C.H. 4,4

Configuration DL:

Maneuver 1: very good response longitudinally, precise; laterally too sensitive to small inputs; roll ratchet; control harmony poor - heavy longitudinally, light laterally. C.H. 4

Maneuver 2: same as #1; sensitive laterally below two g's, better above two g's; longitudinal stick force per g - good. C.H. 4

Maneuver 3: very precise longitudinally; laterally imprecise and the forces are too light; control harmony is bad- heavy longitudinally; light laterally. C.H. 4

Configuration EH:

Maneuver 1: very sluggish lateral response, over correction constantly; PIO tendency laterally; control harmony unsatisfactory. C.H. 7,7

Maneuver 2: high stick forces both axes; laterally sluggish and imprecise under g. C.H. 7,7

Maneuver 3: same as #2; big difference between axes. C.H. 7,7

FIGURE 73 (continued)

Configuration EL:

Maneuver 1: slow initial longitudinal and lateral response with a longitudinal dig in; over correction in both axes; extensive pilot compensation both axes. C.H. 7,7,7

Maneuver 2: too oscillatory both axes; lateral axis most sensitive; control harmony satisfactory; behaves better under g. C.H. 5,5,6

Maneuver 3: too sensitive and oscillatory both axes; cannot make a small precise coorection. C.H. 6,6,7

TABLE X

PILOT COOPER-HARPER RATINGS DATA SUMMARY											
DYNAMICS	PILOT COOPER-HARPER RATING						PILOT COOPER-HARPER RATING				
HIGH ω_{SP}	PILOT	C	D	B		A	PILOT	B	D	C	
$\omega_{SP}=3.8$	FLT. NO.	2145	2147	2150			FLT. NO.	2146	2149	2151	
A	MNVR #1	4	4	5			MNVR #1	4	5	6	
	#2	3	4	6			#2	5	4	5	
$\zeta_{SP}=0.73$	#3	4	5	5			#3	3	4	5.5	
	OVERALL C-H	–	4	6			OVERALL C-H	4	4	–	
LOW ω_{SP}	PILOT	B	C	D		B	PILOT	C	B	D	B
$\omega_{SP}=2.6$	FLT. NO.	2146	2151	2158			FLT. NO.	2145	2148	2149	2150
B	MNVR #1	6	3	4			MNVR #1	5	3	3	3
	#2	6	4	4			#2	4	1	2	4
$\zeta_{SP}=0.63$	#3	4	4.5	4			#3	5	2	2	3
	OVERALL C-H	5	4.5	4			OVERALL C-H	–	2	3	4
BASELINE	PILOT	C	B	D	C	C	PILOT	B	D	C	
$\omega_{SP}=5.6, \zeta_{SP}=.67$	FLT. NO.	2145	2148	2153	2154		FLT. NO.	2146	2149	2151	
$\tau_R=0.36$ C	MNVR #1	2	6	2	5		MNVR #1	5	3	6	
$\omega_{DR}=3.9, \zeta_{DR}=.33$	#2	3	5	2	6		#2	3	3	7	
	#3	3	6	3	6		#3	4	3	6	
	OVERALL C-H	–	5	2	6		OVERALL C-H	–	3	6	
SHORT τ_R	PILOT	C	D			D	PILOT	D			
$\tau_R=0.2$	FLT. NO.	2154	2158				FLT. NO.	2158			
D	MNVR #1	2	4				MNVR #1	4			
	#2	2	4				#2	4			
	#3	4	4				#3	4			
	OVERALL C-H	–	4				OVERALL C-H	4			
LONG τ_R	PILOT	B	D			E	PILOT	B	D	C	
$\tau_R=0.95$	FLT. NO.	2150	2153				FLT. NO.	2148	2155	2154	
E	MNVR #1	7	7				MNVR #1	6	5	8	
	#2	7	6				#2	5	5	6	
	#3	6	7				#3	6	5	7	
	OVERALL C-H	7	7				OVERALL C-H	6	5	7	
STICK FORCE RESPONSE	HEAVY H						LIGHT L				

over the pilots who rated that configuration. These average rankings were compared to the pilot comments and HQDT performance records and were found to properly represent the relative merit of the configurations tested.

Preferred sidestick force response (heavy or light) for each dynamics set, and preferred dynamics for each force response within a control axis were determined for each maneuver by a "voting" scheme. Under this scheme, preference was indicated by a majority or consensus of Cooper-Harper ratings (i.e., two or more pilots assigned better Cooper-Harper ratings to one of the competing configurations). Preferences were not determined where there were insufficient Cooper-Harper ratings to determine a consensus (e.g., the short roll mode time constant case). The "voting" preferences agreed with the average rankings in all cases except the heavy force response/ longitudinal axis comparison for maneuver #3. It should be noted that the "voting" scheme is essentially a ranking scheme of smaller scope that provides no indication of strength of preference and that the ranking scheme provides only an arbitrary and relative indication of strength of preference.

The Cooper-Harper ratings, rankings, and "voting" preferences for each maneuver are presented in Tables XI, XII and XIII. A summary of the trends indicated by these figures is presented in Table XIV. A detailed discussion of these trends and the associated pilot comments follows. The discussion starts with the force response preference within each dynamics set and continues with the dynamics preference for each force response within a control axis.

BASELINE DYNAMICS (C)

A large discrepancy exists in the case of the baseline dynamics (C) as shown by both the ratings and the comments. In the instances where the ratings were poor, the strip chart data traces show a sustained, low magnitude sideslip oscillation and high pilot workload in the lateral axis.

Figures 74 and 75 show strip chart data for the baseline dynamics, heavy force response configuration (CH). Both sets of data were taken during maneuver #3 flown by the same pilot on different days. Note that in the first data set (Figure 74), the sideslip oscillations are minimal, and the pilot assigned this configuration a Cooper-Harper rating of 3. In the second data set (Figure 75), the sustained sideslip oscillations are present, along with a high pilot workload in the lateral axis. This maneuver was given a Cooper-Harper rating of 6. This discrepancy in ratings also occurred for maneuvers #1 and #2.

There were no observable differences in aircraft open loop dynamics or stick force response characteristics which could explain the rating discrepancies, and no determination of cause and effect of this phenomenon could be made. Therefore, the trends indicated by Cooper-Harper ratings or the rankings must be viewed cautiously. Recommend that the sideslip

TABLE XI

TEST RESULTS SUMMARY, MANEUVER #1 AIR-TO-AIR TRACKING						
DYNAMICS	LONGITUDINAL AXIS			LATERAL AXIS		DYNAMICS
HIGH ω_{sp} (A) $\omega_{sp}=9.8$ $\zeta_{sp}=0.73$	5/4/4	4/6/5	C-H RATING PILOT B/C/D	-/2/4	-/-/4	SHORT τ_R (D) $\tau_R=0.2$
	4.5/4/5.5/4.7	3/7.5/8.5/6.3	RANKING PILOT B/C/D/AVG	-/1.5/5.5/3.5	-/-/5.5/5.5	
	↔		VOTING (SEE NOTES)			
MEDIUM ω_{sp} (C) $\omega_{sp}=5.6$ $\zeta_{sp}=0.67$	6/2,5/2	5/6/3	C-H RATING PILOT B/C/D	6/2,5/2	5/6/3	MEDIUM τ_R (C) $\tau_R=0.36$
	7/1.5,5.5/1/3.8	4.5/7.5/2.5/4.8	RANKING PILOT B/C/D/AVG	7/1.5,5.5/1/3.8	4.5/7.5/2.5/4.9	
	↔ ↕		VOTING (SEE NOTES)	↔ ↕	↕	
LOW ω_{sp} (B) $\omega_{sp}=2.6$ $\zeta_{sp}=0.63$	6/3/4	3,3/5/3	C-H RATING PILOT B/C/D	7/-/7	6/8/5	LONG τ_R (E) $\tau_R=0.95$
	7/3/5.5/5.2	15,1.5/5.5/2.5/2.8	RANKING PILOT B/C/D/AVG	9/-/10/9.5	7/9/8.5/8.2	
		↔ ↕	VOTING (SEE NOTES)		↔	
STICK FORCE RESPONSE	HEAVY (H)	LIGHT (L)		HEAVY (H)	LIGHT (L)	STICK FORCE RESPONSE

NOTES: 1) ↔ INDICATES PREFERRED FORCE RESPONSE FOR A GIVEN DYNAMICS

2) ↕ INDICATES PREFERRED DYNAMICS FOR A GIVEN FORCE RESPONSE

TABLE XII

DYNAMICS	LONGITUDINAL AXIS			LATERAL AXIS		DYNAMICS
	TEST RESULTS SUMMARY, MANEUVER #2 AIR-TO-AIR TRACKING					
HIGH ω_{SP}	6/3/4	5/5/4	C-H RATING PILOT B/C/D	-/2/4	-/-/4	SHORT τ_R
(A) $\omega_{SP} = 9.3$	7.5/2.5/5.5/6.2	5/8/5.5/5.5	RANKING PILOT B/C/D/AVG.	-/1/5.5/3.3	-/-/5.5/5.5	(D) $\tau_R = 0.2$
$\zeta_{SP} = 0.73$			VOTING (SEE NOTES)			
MEDIUM ω_{SP}	5/3,6/2	3/7/3	C-H RATING PILOT B/C/D	5/3,6/2	3/7/3	MEDIUM τ_R
(C) $\omega_{SP} = 5.6$	5/2.5,7.5/1.5/4.1	2/9/3/4.7	RANKING PILOT B/C/D/AVG.	5/2.5,7.5/1.5/4.1	2/9/3/4.7	(C) $\tau_R = 0.36$
$\zeta_{SP} = 0.67$	↔ ↕		VOTING (SEE NOTES)	↔ ↕	↕	
LOW ω_{SP}	6/4/4	1,4/4/2	C-H RATING PILOT B/C/D	7/-/6	5/6/5	LONG τ_R
(B) $\omega_{SP} = 2.6$	7.5/4.5/5.5/5.8	1,3/4.5/1.5/2.5	RANKING PILOT B/C/D/AVG.	9/-/10/9.5	5/7.5/8.5/7.0	(E) $\tau_R = 0.95$
$\zeta_{SP} = 0.63$		↔ ↕	VOTING (SEE NOTES)		↔	
STICK FORCE RESPONSE	HEAVY (H)	LIGHT (L)		HEAVY (H)	LIGHT (L)	STICK FORCE RESPONSE

NOTES: 1) ↔ INDICATES PREFERRED FORCE RESPONSE FOR A GIVEN DYNAMICS

2) ↕ INDICATES PREFERRED DYNAMICS FOR A GIVEN FORCE RESPONSE

TABLE XIII

TEST RESULTS SUMMARY, MANEUVER #3 AIR-TO-AIR TRACKING

DYNAMICS	LONGITUDINAL AXIS			LATERAL AXIS		DYNAMICS
HIGH ω_{SP} (A) $\omega_{SP} = 9.8$ $\zeta_{SP} = 0.73$	5/4/5	3/5.5/4	C-H RATING PILOT B/C/D	-/4/4	-/-/4	SHORT τ_R (D) $\tau_R = 0.2$
	6/2.5/8.5/5.7	2/6/5.5/4.5	RANKING PILOT B/C/D/AVG.	-/2.5/5.5/4.	-/-/5.5/5.5	
		↔	VOTING (SEE NOTES)			
MEDIUM ω_{SP} (C) $\omega_{SP} = 5.6$ $\zeta_{SP} = 0.67$	6/3.6/3	4/6/3	C-H RATING PILOT B/C/D	6/3.6/3	4/6/3	MEDIUM τ_R (C) $\tau_R = 0.56$
	8/1.8/2.5/4.9	4/7/2.5/4.5	RANKING PILOT B/C/D/AVG.	8/1.8/2.5/4.9	4/7/2.5/4.5	
	↕	↔	VOTING (SEE NOTES)	↕	↔ ↕	
LOW ω_{SP} (B) $\omega_{SP} = 2.6$ $\zeta_{SP} = 0.63$	4/4.5/4	2,3/5/2	C-H RATING PILOT B/C/D	6/-/7	6/7/5	LONG τ_R (E) $\tau_R = 0.95$
	4/4/5.5/4.5	1,4/5/1/2.8	RANKING PILOT B/C/D/AVG.	8/-/10/9	8/9/8.5/8.5	
		↔ ↕	VOTING (SEE NOTES)		↔	
STICK FORCE RESPONSE	HEAVY (H)	LIGHT (L)		HEAVY (H)	LIGHT (L)	STICK FORCE RESPONSE

NOTES: 1) ↔ INDICATES PREFERRED FORCE RESPONSE FOR A GIVEN DYNAMICS

2) ↕ INDICATES PREFERRED DYNAMICS FOR A GIVEN FORCE RESPONSE

TABLE XIV

PILOT PREFERENCE - TREND SUMMARY

COMPARISON BASE	PREFERENCE
DYNAMICS SET	SIDESTICK FORCE RESPONSE
High ω_{SP} (A)	Heavy (H) - Gross Acquisition
	Light (L) - Fine Tracking
Low ω_{SP} (B)	Light (L)
Baseline (C)	Heavy (H) - Gross Acquisition
	No preference - Fine Tracking
Short τ_R (D)	(Insufficient Data)
Long τ_R (E)	Light (L)

SIDESTICK FORCE RESPONSE	LONGITUDINAL DYNAMICS	LATERAL DYNAMICS
Heavy (H)	Baseline (C)	Baseline (C)
Light (L)	Low ω_{SP} (B)	Baseline (C)

NOTE: Preferences the same for both tasks except as stated.

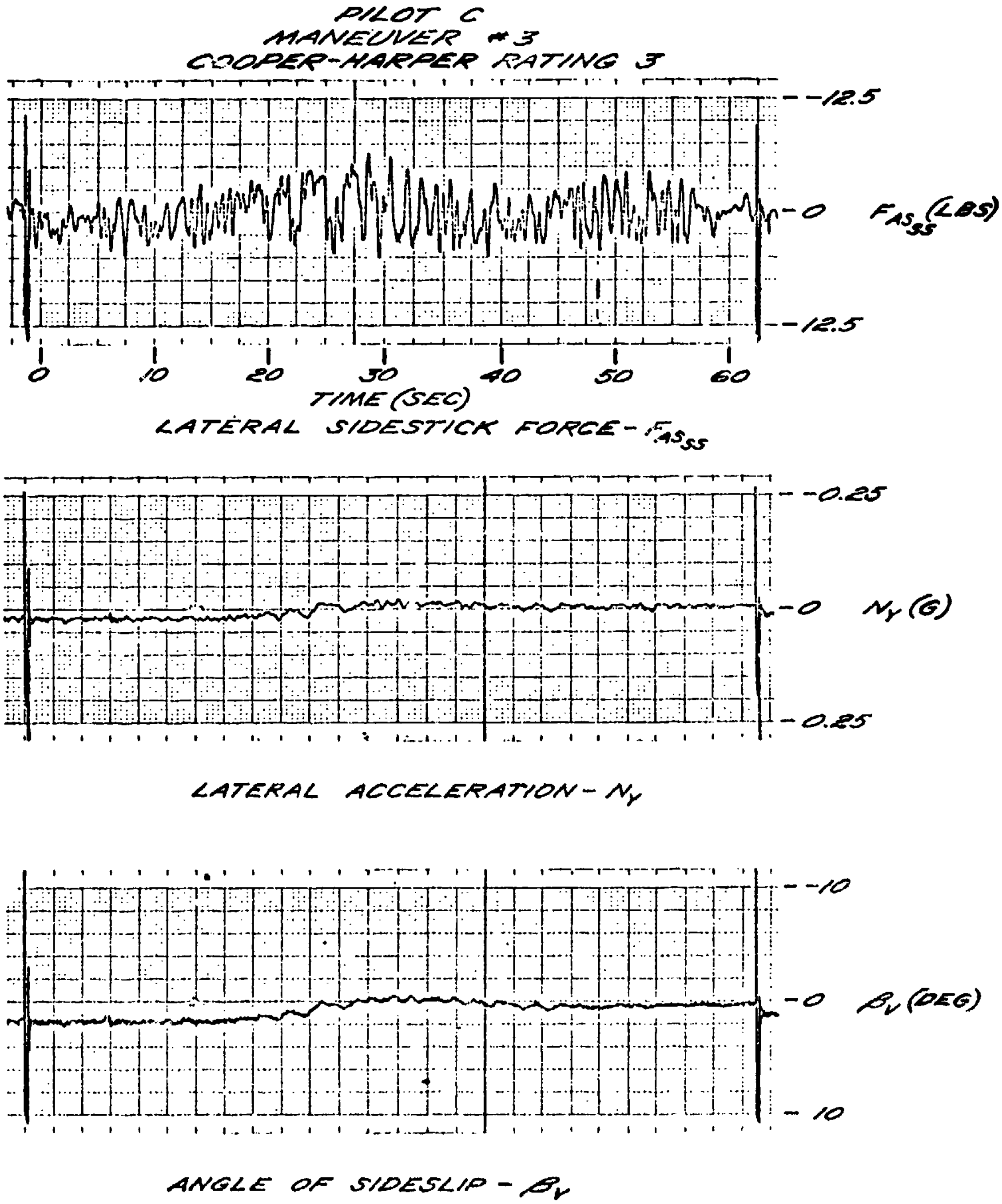


FIGURE 74 Baseline Configuration Strip Chart Records (Without Oscillations)

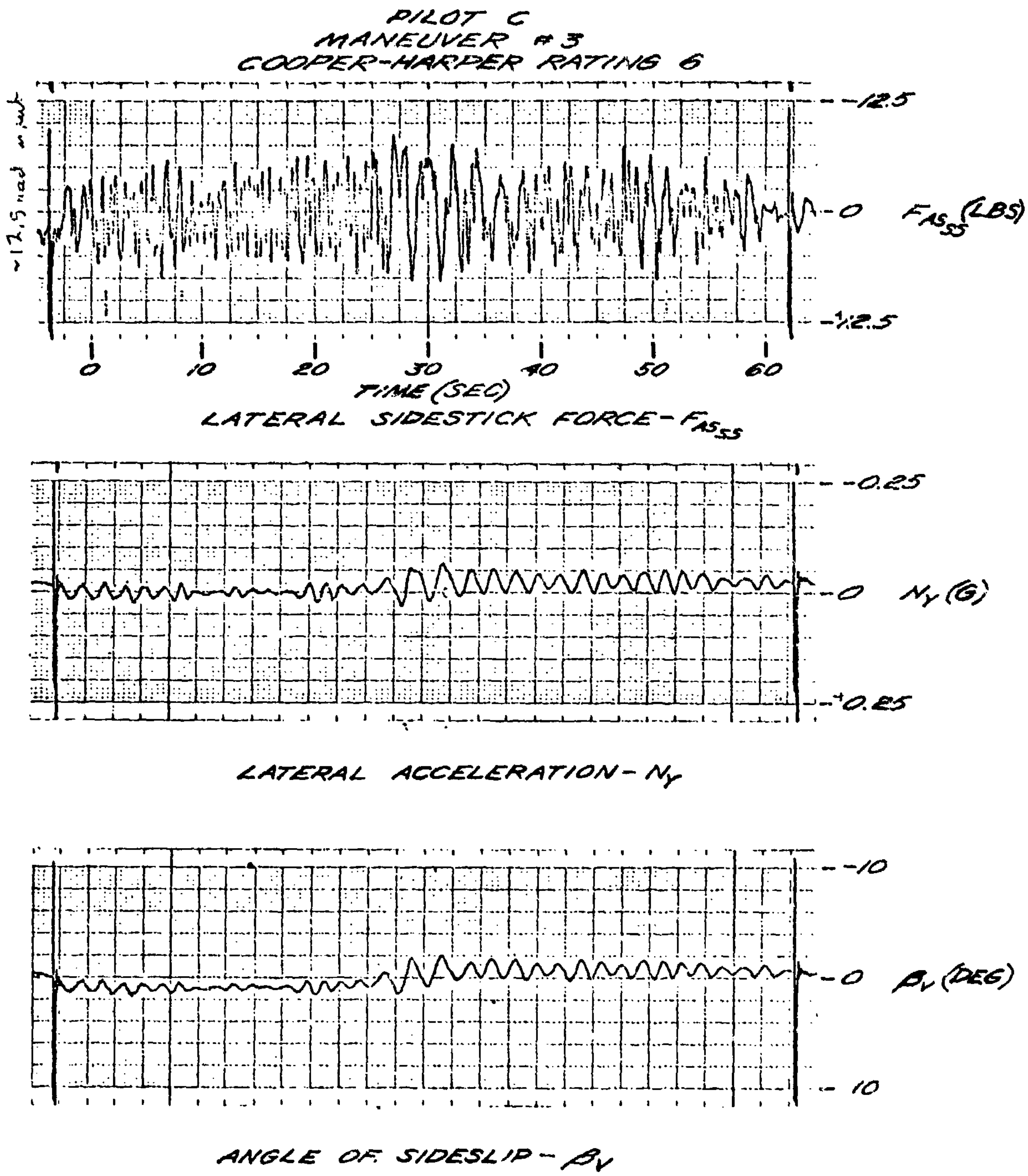


FIGURE 75 Baseline Configuration Strip Chart Records (With Oscillations)

oscillation problem be explored and resolved prior to any further testing. Recommend that further testing with baseline dynamics be conducted to provide an adequate sidestick data base.

LOW SHORT PERIOD NATURAL FREQUENCY (B)

The light force response was clearly preferred by two of the pilots, while the third pilot showed no strong preference. The light force response (Configuration BL) was considered to have very good to excellent longitudinal response and slightly imprecise lateral response. The light stick forces were considered satisfactory. The heavy force response case (Configuration BH) received comments of longitudinal stick too heavy, sluggish but precise longitudinal aircraft response, and slightly imprecise lateral response.

For both force responses, any sluggishness in longitudinal response was more noticeable during gross acquisition; otherwise, the comments were essentially the same for all three maneuvers. It should be noted that the light force response/low short period frequency was the highest rated configuration in this evaluation. However, as shown in Figure 76, the short period frequency actually tested was below Level 1 of the current military specification for centerstick controlled aircraft. Recommend additional testing, at even lower short period frequencies, be conducted to further define the lower boundary of satisfactory short period frequency for sidestick controlled aircraft.

LONG ROLL MODE TIME CONSTANT (E)

The long roll mode time constant dynamics set was the least preferred by all pilots regardless of sidestick force response. The light force response was definitely the more preferred of the two force responses tested. The light force case (Configuration EL) was characterized as having slow initial longitudinal response, followed by dig-in.

The heavy force case (Configuration EH) received comments of very sluggish response, constant overcorrection, and PIO tendencies in the lateral axis. Stick forces were felt to be high in both axes, with the lateral channel being the worse case. The response was too sensitive and oscillatory in both axes, and a small precise movement could not be made, especially in the lateral channel.

As shown in Figure 77, the long roll mode time constant actually tested met Level 1 of the current military specification for centerstick controlled aircraft. With the sidestick controller, the two configurations (EH and EL) did not display satisfactory handling qualities in either gross

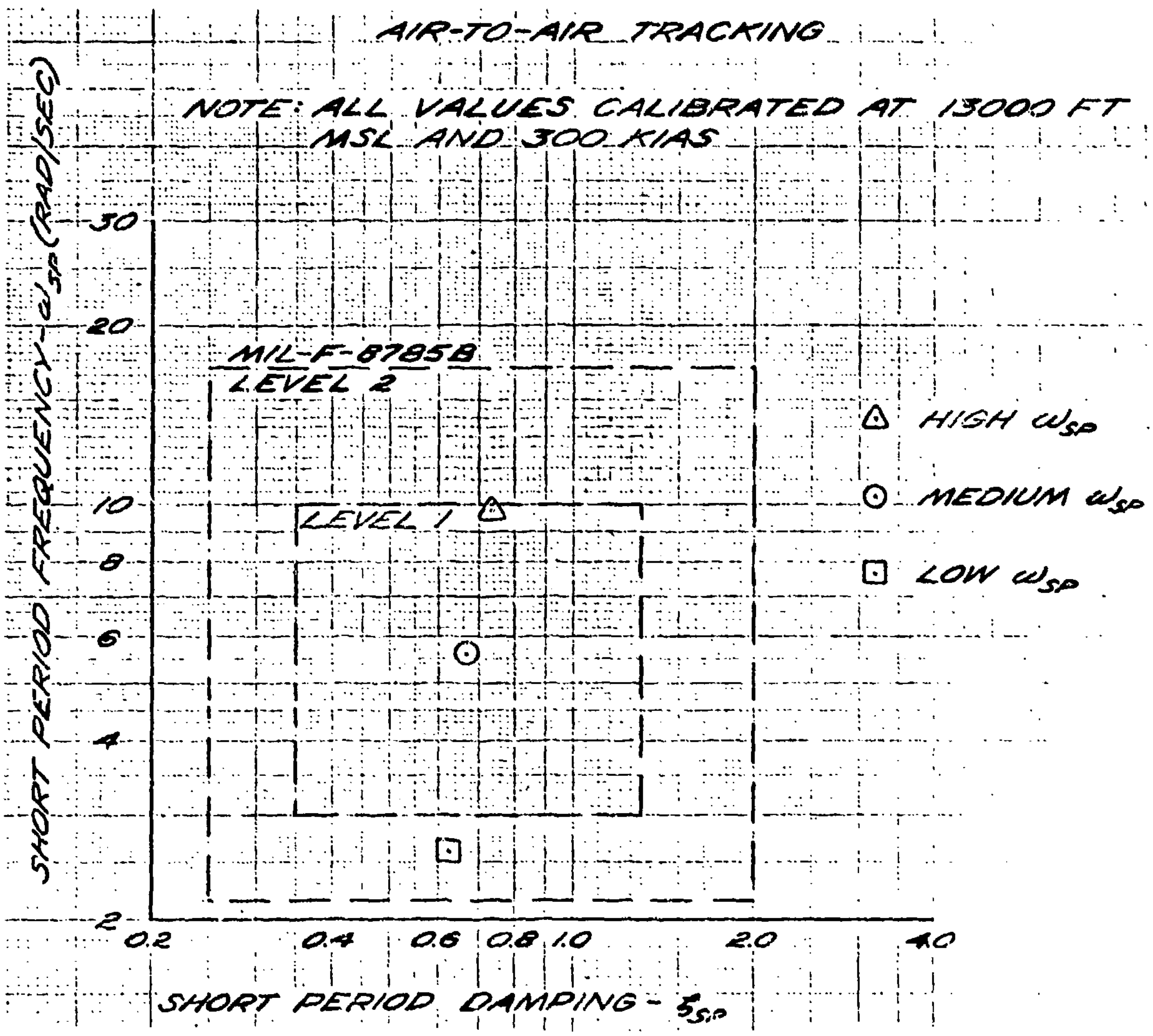


FIGURE 76 SHORT PERIOD DYNAMICS CALIBRATIONS

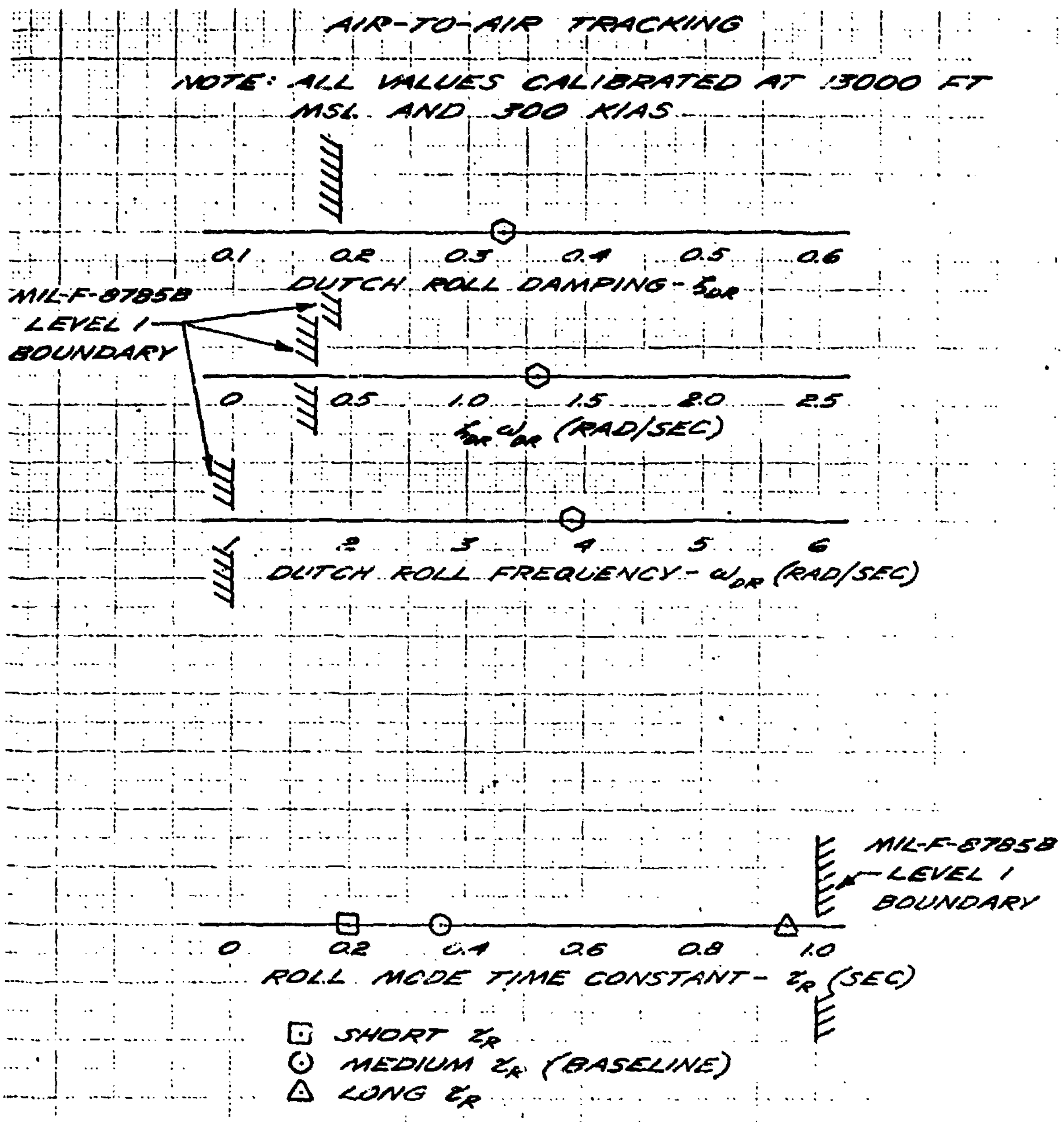


FIGURE 77 Dutch Roll and Roll Mode Time Constant Dynamics Calibrations

acquisition or fine tracking. Recommend additional testing be conducted at roll mode time constants between 0.4 and 0.9 seconds to further define the upper boundary of satisfactory roll mode time constants for sidestick controlled aircraft.

OTHER DYNAMICS

Since the short roll mode time constant configurations with both heavy and light force response configurations (DH and DL) were evaluated by only one pilot who assigned equal ratings to the two configurations, there were insufficient data to determine a preferred force response.

For the high short period frequency (A), the heavy force response was favored for gross acquisition, and the light force was the main pilot comment for the heave force response, whereas imprecise and oscillatory longitudinal response was the prime comment for the light force response case. These force response preferences were not very strong in terms of either ratings or comments.

Due to the inconclusive results for the short roll mode time constant and high short period frequency configurations, recommend that further testing of these dynamics be conducted to provide an adequate sidestick data base.

LONGITUDINAL AXIS

Given the heavy sidestick force response, the baseline medium short period frequency configuration (C) was definitely the most preferred by all pilots for both the gross acquisition and fine tracking tasks. With the light force response, the pilots found the baseline longitudinal response less damped and more oscillatory.

Given the light sidestick force response, the low short period frequency configuration (B) was definitely the most preferred by all pilots for both the gross acquisition and fine tracking tasks. For the low short period frequency with the heavy force response, the pilots commented that the longitudinal stick forces were too high, but the longitudinal response was still precise.

LATERAL AXIS

Given either the heavy or light sidestick force response, the baseline roll mode time constant configuration (C) was definitely the most preferred by all pilots for both gross acquisition and fine tracking tasks. The short roll mode time constant (D) was described as too sensitive with a tendency to overcontrol. The long roll mode time constant (E) was described as too sluggish and also led to overcontrol. These comments were essentially the same for all three maneuvers.

For the two force responses used in this evaluation, pilot preference for force response was not constant throughout all dynamic sets, but changed with variations in dynamics for both the gross acquisition and fine tracking tasks. In both cases of strong and conclusive pilot preferences, the low short period frequency and the long roll mode time constant, the force response preferences were the same for both the gross acquisition and fine tracking tasks. Since the two force responses used in this evaluation represent only a small portion of the feasible sidestick force response and deflection gradient combinations, it is recommended that further testing with the same dynamic sets and other sidestick force responses and deflection gradients should be conducted.

CONCLUSIONS AND RECOMMENDATIONS

All the specific test objectives of the NT-33A test project were achieved. Overall analysis of the results showed pilot preference for sidestick force response characteristics was influenced by changes in aircraft dynamics during air-to-air gross acquisition and fine tracking tasks. For both the low short period frequency and the long roll mode time constant, the force response preferences were the same for both the gross acquisition and fine tracking tasks. For the other dynamics tested, where the results were less conclusive, force response preferences were not the same for both tasks.

A large discrepancy existed in the case of the baseline dynamics (C), as illustrated by both the pilots' comments and ratings. Unexplainable sideslip oscillations and high pilot workload accompanied the poor ratings and were absent for the good ratings.

1. Recommend that the sideslip oscillation problem be explored and resolved prior to any further testing.

2. Recommend that further testing with baseline dynamics be conducted to provide an adequate sidestick data base.

The low short period frequency/light force response combination was the highest rated configuration in this evaluation; however, the actual short period frequency tested was below Level 1 of the current MIL-F-8785B(ASG).

3. Recommend additional testing, at even lower short period frequencies, be conducted to further define the lower boundary of satisfactory short period frequency for sidestick controlled aircraft.

The long roll mode time constant was unsatisfactory and the least preferred configuration tested, regardless of the force response used. The long roll mode time constant actually tested met Level 1 of the current MIL-F-8785B(ASG).

4. Recommend additional testing be conducted, at roll mode time constants between 0.4 and 0.9 seconds, to further define the upper boundary of roll mode time constants for sidestick controlled aircraft.

The test results were inconclusive for the short roll mode time constant and the high short period frequency configurations.

5. Recommend that further testing of these dynamics be conducted to provide an adequate sidestick data base.

The two force responses used in this evaluation represent only a small portion of the feasible sidestick force response and deflection gradient combinations.

6. Recommend that further testing with the same dynamic sets and other sidestick force responses and deflection gradients be conducted.

PILOT BACKGROUND INFORMATION[1]

Pilot C: LCDR W.W. Copeland

F-4 (B/N/J) - 2000 hrs/SEA combat tour
Mission: Air-to-Air

F-5E - 50 hrs/Top Gun Instructor
Mission: Air-to-Air

A-4 - 300 hrs/Top Gun Instructor

Pilot D: Major M. Dvir

F-4E - 650 hrs/combat
Mission: Air-to-Air/Air-to-Ground

A-4H - 350 hrs/combat/instructor
Mission: Air-to-Ground

FUGA-MAGISTER - 700 hrs (550 hrs IP)
Mission: Air-to-Air Trainer

VAUTOUR - 650 hrs/combat
Mission: Air-to-Ground

Pilot B: Capt R.T. Banholzer

F-4E - 2000 hrs (800 hrs IP)/Fighter Weapons School
Mission: Air-to-Air/Air-to-Ground

[1] Pilot background information is listed in order of most recent operational experience.

APPENDIX F

TECHNICAL RESULTS AND DISCUSSION FROM USAF TEST PILOT SCHOOL LETTER REPORT - 5 June 1979 "Limited Flight Evaluation of the Effect of Sidestick Force/Deflection/Response Characteristics on Control Harmony of the NT-33A Aircraft" by Donald A. Cornell, Captain, USAF; Richard J. Duprey, 1Lt, USAF; David W. Minto, Captain, USAF; Leo V. Seeber, Captain, USAF and Edwin A. Thomas, Captain, USAF.

ABSTRACT

Test Pilot School Class 78B conducted a limited investigation to determine the effect of sidestick gradient ratios on the handling qualities of sidestick controlled aircraft during specific air-to-air tasks. The test aircraft, AFFDL's variable stability NT-33A, was configured with a baseline set of aircraft dynamics and specific longitudinal force/response and lateral sidestick force/deflection/response combinations. Pilot comments and Cooper-Harper ratings were analyzed for all configurations.

The test results show a pilot preference for light nonlinear longitudinal force/response gradients, low short-period natural frequency, medium lateral sidestick force/deflection gradients, and a heavy lateral force/response gradient with a small nonlinearity. The total project consisted of 47 calibration, data, target support, and practice sorties totalling 66.6 hours flown at the Air Force Flight Test Center, Edwards AFB, California from 25 April to 18 May 1979.

OBJECTIVES

The overall test objective was to determine pilot preference for lateral sidestick controller force and deflection gradients tested in conjunction with specified values of stick force per "g" and aircraft dynamics.

There were three specific test objectives:

1. Phase I attempted to determine pilot preferences for lateral sidestick controller force-deflection-response gradients with both a light and medium dual gradient stick force "g" during specific air-to-air, rudder-free acquisition and tracking tasks.

2. Phase II attempted to determine pilot preference for control harmony based on the optimum lateral gradients from Phase I, for each longitudinal configuration, but using new light and medium linear and dual longitudinal gradients during specific air-to-air, rudder-free acquisition and tracking tasks.

3. Phase III attempted to verify pilot preference for control harmony based on a single optimum configuration selected from Phases I and II during specific air-to-air tasks using rudder.

Additionally, data were collected to permit determination and verification by another agency of acceptable digital-type transport time delays during approach and landing tasks.

TEST METHODS AND CONDITIONS

During all air-to-air testing, the aircraft dynamics (except ωn_{sp}) were fixed and are shown in Table XV. The longitudinal force/deflection gradient was maintained at 1.07 pounds/degree. Twelve configurations of stick force/deflection/response gradients were evaluated during Phase I. These configurations are presented in Table XVI and Figure 78. Configurations C and I, Table XVI were not evaluated. Four configurations of stick force/deflection/response gradients were evaluated during Phase II and are presented in Table XVII. One configuration, representing the optimum configuration from Phases I and II was evaluated during Phase III. Table XVIII presents this configuration.

Test points were selected to allow equal pilot exposure to each configuration. Points were sequenced to minimize biases due to the pilot learning curve effect and due to contrast between configurations. Each pilot flew the same sequence, and points were repeated to verify initial evaluations. Within these considerations, points were presented to the pilots in a scrambled order, and project pilots were not aware of the configurations being flown. Except for two sorties during which time constraints required early termination, three test configurations per sortie

TABLE XV

NT-33 DYNAMICS

PARAMETER	NOMINAL	ACTUAL
ωn_{sp}	2.6/5.6	2.7/6.1
ζ_{sp}	0.7	0.7
n_z/α (g/rad)	29	22
ω_d (rad/sec)	3.9	3.2
ζ_d	0.33	0.47
ϕ/β	2	2.8
τ_r (sec)	0.36	0.30
ω_p (rad/sec)	0.15	0.08
ζ_p	.05	<0.1
τ_s	∞	∞
F_{es}/g (lb/g)*	5/10	5.0/10.75
F_{es}/δ_{es} (lb/deg)	1.19	1.07

* Longitudinal force-response gradients halve at four pounds absolute.

TABLE XVI

PHASE 1 TEST CONFIGURATIONS

Configuration	Long Force* Response Gradient (lb/g)	$\omega_{n_{sp}}$ (rad/sec)	Lateral Force Deflection Gradient (lb/deg δ_{as})	Lateral Force** Response Gradient
A	5 (Light)	2.7 (low)	.4	I
B			.4	II
C			.95	I
D			.95	II
E			.95	III
F			.95	IV
G			2.4	III
H	10 (Medium)	6.1 (medium)	.4	I
I			.4	II
J			.95	I
K			.95	II
L			.95	III
M			.95	IV
N			2.4	III

* Longitudinal force-response gradients halve at four pounds absolute. ** See Figure 78.

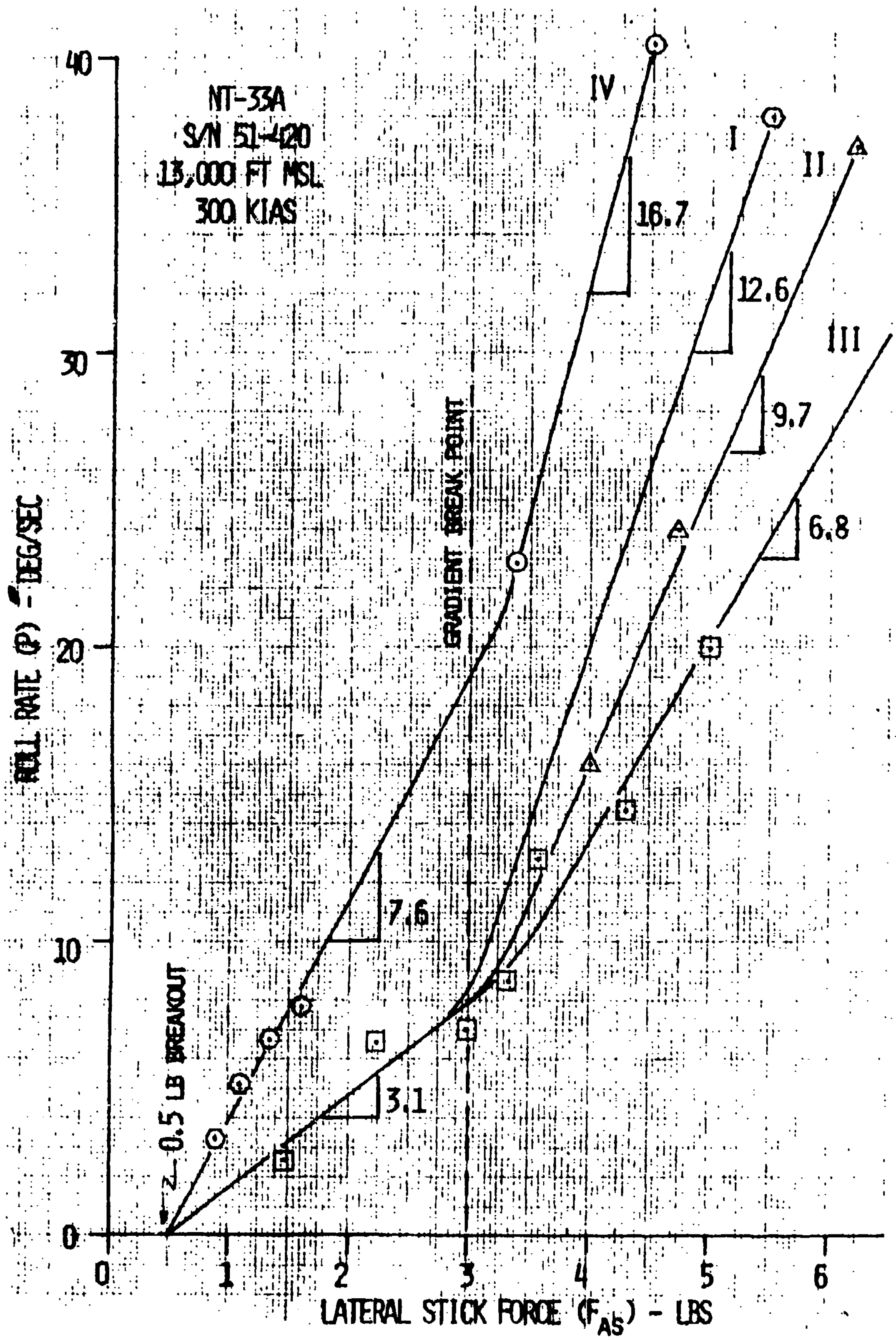


FIGURE 78. LATERAL FORCE-RESPONSE GRADIENTS

TABLE XVIII

PHASE III TEST CONFIGURATION

Longitudinal Force* Response Gradient (lb/g)	$\omega_{n_{sp}}$ (rad/sec)	Lateral Force Deflection (lb/deg)	Lateral force/response (lb/deg/sec)	
			Before break	Ratio After break
5 dual	2.7	0.95	0.3	.46:1

* Dual longitudinal force response gradient halved at 4 pounds absolute.

TABLE XVII

PHASE II TEST CONFIGURATIONS

Configuration	Long Force* Response Gradient (lb/g)	$\omega_{n_{sp}}$ (rad/sec)	Lateral Force Deflection (lb/deg)	Lateral force/response (lb/deg/sec)	
				Before break	Ratio After break
AA	5 dual	2.7	0.95	0.3	.46:1
BB	5 linear	2.7	0.95	0.3	.46:1
CC	11 dual	6.1	2.4	0.3	.46:1
DD	11 linear	6.1	2.4	0.3	.46:1

* Dual longitudinal force response gradients quartered at four pounds absolute.

were evaluated for each task. Seven sorties per pilot were flown during Phase I, two sorties per pilot during Phase II and one sortie was flown during Phase III.

Each air-to-air task began with the NT-33A trimmed for level flight at 13,000 feet pressure altitude and 300 KIAS. The NT-33A was not re-trimmed during the tasks. The tasks were performed without using the rudder (except for Phase III) and using a fixed gunsight depression of 55 mils.

Three air-to-air tasks were flown to evaluate the gross acquisition and fine tracking capabilities of each configuration. Maneuver #1 was begun with the NT-33A in trail at 1500 feet and co-airspeed. At this time the T-38A initiated a 2g, 300 KIAS, level turn. The evaluation pilot would wait till the T-38A crossed the canopy bow, call "hack", and aggressively maneuver to place and keep the pipper within 10 mils of the T-38A tailpipe junction. At this time, the evaluation pilot would call "tracking". When the evaluation pilot called "clear to reverse", the T-38A would perform an unloaded level reversal to a 2g, 300 KIAS level turn in the opposite direction. The maneuver would then be repeated in this direction until the evaluation pilot called "knock it off".

Maneuver #2 was begun with the NT-33A in trail at 1500 feet, co-airspeed, and both aircraft in 10° of bank. With the evaluation pilot tracking, the T-38A within 10 mils, the T-38A would initiate a wind-up turn from 1 to 3.5g at a maximum onset rate of .2g per second. The evaluation pilot would attempt to precisely, persistently, and aggressively keep the pipper centered on the T-38A tailpipe junction. After reaching 3.5g, the T-38A would maintain 3.5g until the evaluation pilot considered the maneuver to be complete. Maneuver #2 was accomplished in each direction.

Maneuver #3 was begun with the NT-33A in trail at 1500 feet, co-airspeed, with each aircraft in a 30° bank turn. With the evaluation pilot tracking the T-38A within 10 mils, the T-38A would initiate a slow, smooth, modified "lazy 8" maneuver utilizing a constant 2g with bank angle changes of $\pm 90°$ and maximum pitch angles of ± 15 degrees. The evaluation pilot would attempt to precisely, persistently, and aggressively keep the pipper centered on the tailpipe junction. Both aircraft accepted the resulting airspeed loss and did not attempt to maintain 300 KIAS throughout the maneuver. The maneuver was continued until the evaluation pilot considered it complete.

At the conclusion of the evaluation of each configuration the evaluation pilot completed the inflight comment card. The NT-33A magnetic tape system, audio recorder, and gun camera were operated during each task.

Each evaluation pilot was thoroughly debriefed as soon as possible after landing in accordance with the mission debriefing guide.

TEST RESULTS AND ANALYSIS

Pilot comments and Cooper-Harper ratings were provided for each test configuration. Condensed pilot comments and a summary of Cooper-Harper ratings are provided in Tables XIX through XXII. Pilot backgrounds are given in Table XXIII.

The results of this test were analyzed phase by phase in an attempt to arrive at general observations about the merit of various configurations.

Phase I

Longitudinal Force-Response Gradients and Dynamics

The test configurations with a low short period natural frequency of 2.7 rad/sec and a light force-response gradient of 5 lb/g were generally found to have smooth, precise pitch response. However, the test configurations with a medium ωn_{sp} of 6.1 rad/sec and a medium force response gradient of 11 lb/g exhibited ± 5 mil pitch bobbles during fine tracking. Pilots also commented that longitudinal sidestick forces were too heavy. There is a definite interaction between sidestick force and deflection and it is possible that the noted pitch bobble and perception of high longitudinal force could be eliminated by varying the sidestick longitudinal force-deflection gradient. Since the ωn_{sp} and force-response gradient in question are in the middle of the centerstick controller Level 1 requirements of MIL-F-8785B, further studies should be conducted with this configuration. If an acceptable sidestick force-deflection gradient cannot be found for this configuration, it may be determined that ωn_{sp}, F_{es}/g, or both for sidestick-controlled aircraft should be lower than is generally deemed middle-of-the-envelope for centerstick controlled aircraft.

Lateral Force-Deflection Gradients

Three lateral force-deflection gradients were evaluated: 0.4 lb/deg (large), 0.95 lb/deg (medium), and 2.4 lb/deg (small). The large lateral sidestick deflections were found to result in poor harmony for both longitudinal configurations. Pilots commented that lateral deflections were excessive and caused some inadvertent pitch inputs during tracking.

Medium lateral deflections were found to be satisfactory and well-matched with longitudinal deflections for the low short period/light stick force (low/light) longitudinal configuration. For the medium short period/medium stick force (medium/medium) longitudinal configuration, the medium lateral deflections seemed mismatched. Pilots commented that control harmony was unsatisfactory.

Small lateral sidestick deflections were generally perceived as high lateral forces although the force-response gradient was unchanged. For the low/light longitudinal configuration, lateral forces were perceived

TABLE XIX

PILOT RATINGS AND CONDENSED COMMENTS FOR PHASE I CONFIGURATIONS

Stick Force/G* Short Period Natural Frequency	Sidestick Force/Deflection Gradient	Sidestick Initial Force/Response Gradient	Sidestick Force/Response** Ratio After Break	Pilot Ratings
F_{es}/g = 5 lb/g (light) $\omega_{n_{sp}}$ = 2.7 rad/sec (low) Light longitudinal forces Smooth, precise pitch response	F_{as}/δ_{as} = 0.4 lb/deg (large deflection) Large lateral deflections resulted in poor harmony	F_{as}/p = 0.3 lb/deg/sec Unprecise for larger lateral inputs. Directional Oscillations	0.25:1	7
		F_{as}/p = 0.3 lb/deg sec Lateral forces light. Slow directional response to lateral inputs.	0.32:1	6,5
	F_{as}/δ_{as} = 0.95 lb/deg (medium deflection) Satisfactory Well matched w/ longitudinal deflections	F_{as}/p = 0.3 lb/deg/sec Not tested.	0.25:1	-
		F_{as}/p = 0.3 lb/deg/sec Aileron snatch. Lateral forces too heavy. Roll response too fast for small inputs. Overshoots.	0.32:1	7,5
		F_{as}/p = 0.3 lb/deg/sec Lateral forces slightly higher than longitudinal harmony satisfactory. Lateral forces tended to smooth out directional corrections	0.46:1	5,5,4.5,4,4
		F_{as}/p = 0.13 lb/deg/sec Directional response too small for small lateral inputs. Tendency to overcontrol laterally.	0.46:1	7,4,3,6
	F_{as}/δ_{as} = 2.4 lb/deg (small deflection) Directional pipper wanders during fine tracking	F_{as}/p = 0.3 lb/deg/sec Harmony unsatisfactory because of high lateral forces. Lateral inputs caused inadvertent longitudinal inputs. Pitch overshoots at higher g.	0.46:1	6,5

* Sidestick longitudinal stick force/g gradient halves at F_{es} = 4 lbs absolute.
** Break in sidestick lateral force/response ratio occurs when F_{as} = 3 lbs absolute.

TABLE XIX (continued)

PILOT RATINGS AND CONDENSED COMMENTS FOR PHASE I CONFIGURATIONS (Continued)

Stick Force/G* Short Period Natural Frequency	Sidestick Force/Deflection Gradient	Sidestick Initial Force/Response Gradient	Sidestick Force/Response** Ratio After Break	Pilot Ratings
F_{es}/g = 11 lb/g (medium) $\omega_{n_{sp}}$ = 6.1 rad/sec (medium) Longitudinal forces too heavy. Constant ± 5 mil pitch bobble during fine tracking.	F_{as}/δ_{as} = 0.4 lb/deg (Large deflection) Large lateral deflections caused inadvertent pitch inputs. Harmony unsatisfactory.	F_{as}/p = 0.3 lb/deg/sec Lateral response much too slow. Slow directional oscillations.	0.25:1	7
		F_{as}/p = 0.3 lb/deg/sec Not tested.	0.32:1	-
	F_{as}/δ_{as} = 0.95 lb/deg (Medium deflection) Generally satisfactory. Some configurations had mismatched lateral and longitudinal sidestick deflections.	F_{as}/p = 0.3 lb/deg/sec Lateral response too fast for small corrections. Jerky roll response. Unprecise directional tracking.	0.25:1	5
		F_{as}/p = 0.3 lb/deg/sec Lateral forces too high. No finesse in directional tracking. Lateral deflections too large.	0.32:1	5,5
		F_{as}/p = 0.3 lb/deg/sec Lateral forces higher than longitudinal. Lateral inputs caused inadvertent longitudinal inputs. Harmony unsatisfactory under higher g.	0.46:1	6,5,7
		F_{as}/p = 0.13 lb/deg/sec Lateral response unprecise. Longitudinal inputs caused inadvertent lateral inputs at higher g. Harmony unsatisfactory. Jerky lateral response.	0.46:1	6,5,7
	F_{as}/δ_{as} = 2.4 lb/deg (Small deflection) Directional pipper wander during fine tracking.	F_{as}/p = 0.3 lb/deg/sec Lateral forces a little high. Smooth lateral response.	0.46:1	4,6,4,5

* Sidestick longitudinal stick force/g gradient halves at F_{es} = 4 lbs absolute.

** Break in sidestick lateral force/response ratio occurs when F_{as} = 3 lbs absolute.

TABLE XX PILOT RATINGS AND CONDENSED COMMENTS FOR LIGHT LONGITUDINAL PHASE II CONFIGURATIONS

$F_{es}/g = 5$ lb/g $\quad$ $F_{as}/\delta_{as} = 0.95$ lb/deg $\quad$ $\omega_{n_{sp}} = 2.7$ rad/sec

$F_{as}/p = .3$ lb/deg/sec

(Ratio after break 0.46:1)

Longitudinal Gradient	Linear	Nonlinear 0.25:1 After Break at 4 lb
Pilot Comments	Good response in both axes. Easy to track tgt, but small directional pipper wander during fine tracking. Lateral forces slightly high but satisfactory. Control harmony satisfactory.	Quick longitudinal response. 2 to 3 mil pitch bobble during fine tracking above 2g. Longitudinal forces too light. Lateral inputs caused inadvertent longitudinal input control harmony unsatisfactory.
Pilot Ratings	4,4	5,4

TABLE XXI PILOT RATINGS AND CONDENSED COMMENTS FOR MEDIUM LONGITUDINAL PHASE II CONFIGURATINS

$F_{es}/g = 11$ lb/g $\quad$ $F_{as}/\delta_{as} = 0.8$ lb/deg $\quad$ $\omega_{n_{sp}} = 6.1$ rad/sec

$F_{as}/p = .3$ lb/deg/sec

(Ratio after break 0.46:1)

Longitudinal Gradient	Linear	Nonlinear 0.25:1 After Break at 4 lb
Pilot Comments	Longitudinal Response too slow. Longitudinal and lateral forces too high. Deflections both axes too large. Heavy forces were tiring.	Quick longitudinal response. 2 to 3 mil pitch bobble during fine tracking above 2g. Longitudinal deflections were large. Sidestick had springy longitudinal feel. Tendency to overcontrol g. Control harmony unsatisfactory.
Pilot Ratings	4,5	4,5

TABLE XXII

PILOT RATING AND CONDENSED PILOT COMMENTS FOR AIR-TO-AIR TASKS WITH USE OF RUDDERS (PHASE III)

F_{es}/g = 5 lb/g* (halved at F_{es} = 4 lb absolute $\omega_{n_{sp}}$ = 2.7 rad/sec

F_{as}/δ_{as} = 0.95 lb/deg

F_{as}/p = 0.3 ob/deg/sec

Ratio 0.46:1 after break at F_{as} = 3 lb absolute

PILOT COMMENTS: Lateral and longitudinal forces and deflections were satisfactory. Control harmony satisfactory. Responsive and precise in both axis. Rudder pedal forces too light. Pipper very sensitive directionally to rudder pedal deflections. In general, any use of rudder degraded the configuration. Zero sideslip was essential to successful tracking.

PILOT RATINGS: 5,4

TABLE XXIII

PILOT BACKGROUND INFORMATION

Captain Donald A. Cornell

A-7 (D/E) 1500 hrs/SEA combat tour
Navy Exchange Tour
Mission: Air-to-Ground

F-100 500 hrs/SEA combat tour
Mission: Air-to-Ground

Captain Edwin A. Thomas

A-7D - 850 hours
Mission: Air-to-Ground

F-4E - 450 hours (Weapon Systems Officer)
Mission: Air-to-Air; Air-to-Ground

F-105G - 430 hours (Electronic Warfare Officer)/combat
Mission: Wild Weasel

as too high and caused inadvertent pitch inputs. Pilots commented that control harmony was unsatisfactory. For the medium/medium longitudinal configuration, lateral forces were perceived as satisfactory but a little high. Pilots commented that lateral response was smooth. During all configurations tested with the small lateral sidestick deflections, a small (±2 mil) pipper wander was noted by the pilots during fine tracking. Further testing should be conducted using the medium/medium longitudinal configuration in conjunction with small lateral deflections to better determine an optimum longitudinal and lateral force-deflection gradient combination.

Lateral Force-Response Gradients

Lateral force-response gradients of 0.3 lb/deg/sec (medium response) and 0.13 lb/deg/sec (fast response) were evaluated. The test configurations with the fast response were generally unsatisfactory. With the light/low longitudinal configurations, there was a tendency to overcontrol laterally, while with the medium/medium longitudinal configuration, control harmony was unsatisfactory. Longitudinal inputs caused inadvertent lateral inputs, particularly at load factors greater than 2. Pilots commented that lateral response in both longitudinal configurations was jerky. The medium lateral response was generally perceived as satisfactory by the pilots as long as the control harmony caused by other parameters was satisfactory.

Lateral Force-Response Gradient Non-Linearities

Changes in the slope of the lateral force-response gradient to 0.46:1 (small), 0.32:1 (medium), and 0.25:1 (large) were tested. Each of the slope changes occurred at 3 pounds F_{as} absolute. Both the medium and large slope changes seemed to hamper the pilots' ability to predict aircraft roll performance. This was often perceived as roll sensitivity or jerkiness. The small slope change configurations were satisfactory. The tested slope changes were never recognized in flight by the project pilots. One purpose of lateral force-response non-linearities is to produce lateral responsiveness for gross acquisition tasks while increasing lateral predictability during fine tracking. Since the pilots perceived roll rate more readily than stick force, changes in lateral force-response gradients based on a specific roll rate might be more appropriate and should be investigated. Using this type of non-linear gradient, all roll rates normally used for fine tracking could be commanded in the same linear region of the force-response gradient.

Phase II

Longitudinal Non-Linearity

Longitudinal force-response (lb/g) gradients were investigated in conjunction with the optimum lateral test configurations from Phase I

(see Table XVII). Changes in the slope of longitudinal force-response gradients of 1:1 (linear), 0.5:1 (medium), and 0.25:1 (large) were tested for both light/low and medium/medium longitudinal configurations. Each slope change occurred at 4 lbs F_{es} absolute.

The linear longitudinal force-response gradient was clearly unacceptable for medium/medium longitudinal configurations due to excessively high longitudinal stick forces. For the light/low longitudinal configurations, the linear gradient was satisfactory.

The medium longitudinal force-response gradient change was the longitudinal test configuration during all of Phase I. As stated previously, this was satisfactory for the light/low test configuration while pitch bobbles occurred with the medium/medium configuration.

The large longitudinal force-response gradient change was found to impact on the pilots' ability to predict aircraft longitudinal response. With the light/low longitudinal configuration, pitch bobbles occurred during fine tracking with the large gradient change. With the medium/medium longitudinal configuration, the pilots' previously mentioned pitch bobble problem increased. Pilots commented in both cases that there was an apparent stick-force lightening and a tendency for the aircraft to dig in at higher g's.

As noted for lateral gradient changes, longitudinal force-response gradient changes based on aircraft response rather than stick force should be investigated.

Phase III

During Phase III, the optimum configuration found during Phases I and II (see Table XVIII) was tested while allowing the pilot to use rudder inputs to attempt to enhance his tracking. It was found with the directional configuration of the NT-33A that the use of rudder during fine tracking detracted from pilot performance. This conclusion is limited only to the configuration tested. Further testing should be conducted to investigate directional force-response changes on an optimum longitudinal/lateral configuration.

CONCLUSIONS AND RECOMMENDATIONS

The lateral configurations found to have the best handling qualities during Phase I had the following parameters:

F_{as}/as (lb/deg)	F_{as}/p before break (lb/deg/sec)	F_{as}/p ratio after break
0.95	0.3	0.46:1
2.4	0.3	0.46:1

The configuration found to have the best overall handling qualities of all configurations tested had the following parameters:

F_{es}/g (lb/g)	n_{sp} (rad/sec)	F_{as}/δ_{as} (lb/deg)	F_{as}/p before break (lb/deg/sec)	F_{as}/p ratio after break
5	2.7	0.95	0.3	0.46:1

In general, those test configurations with a 2.7 rad/sec short period and a force-response gradient of 5 lb/g were satisfactory. Configurations with a 6.1 rad/sec short period and force-response gradient of 11 lb/g were unsatisfactory with heavy forces and small pitch bobbles noted.

1. Since 6.1 rad/sec and 11 lb/g are in the middle of the centerstick controller Level 1 requirement of MIL-F-8785B, further studies should be conducted with this configuration.

The lateral force-deflection gradient of 0.4 lb/deg resulted in poor control harmony and inadvertent pitch inputs. The lateral force-deflection gradient of 0.95 lb/deg resulted in satisfactory control harmony with the light longitudinal configuration, but poor harmony with the medium longitudinal configuration. The lateral force-deflection gradient of 2.4 lb/deg was generally found to be too high and control harmony was unsatisfactory with the light longitudinal configuration. Lateral forces were perceived as high but satisfactory and lateral response was smooth with the medium longitudinal configuration.

2. Further testing should be conducted using the longitudinal configuration of 6.1 rad/sec short period and 11 lb/g force-response gradient in conjunction with small lateral deflections to better determine an optimum longitudinal and lateral force-deflection gradient combination.

Test configurations with a 0.13 lb/deg/sec lateral force-response gradient were generally unsatisfactory. With the light longitudinal configurations, there was a tendency to overcontrol laterally, while with the medium longitudinal configuration, control harmony was judged unsatisfactory. Test configurations with a 0.3 lb/deg/sec lateral force-response gradient was generally perceived as satisfactory.

Changes in the slopes of the lateral force-response gradients to 0.32:1 and 0.25:1 at 3 pounds absolute seemed to hamper the pilots' ability to predict aircraft roll performance. Change in slope to 0.46:1 at 3 pounds absolute was judged satisfactory.

3. Changes in lateral force-response gradients based on a specific roll rate rather than sidestick force should be investigated.

The linear longitudinal force-response gradient of 11 lb/g was unacceptable due to high longitudinal stick forces. The linear 5 lb/g gradient was judged acceptable.

The longitudinal force-response gradient change of 0.25:1 at 4 pounds absolute was judged unsatisfactory in conjunction with both the 5 and 11 lb/g longitudinal force-response gradient, due to pitch bobbles and an apparent stick force lightening at higher g.

4. Longitudinal force-response gradient changes based on aircraft response rather than stick force should be investigated.

With the directional characteristics of the NT-33A as configured, the use of rudder during fine tracking detracted from pilot performance.

5. Further testing should be conducted to investigate directional force-response changes on an optimum longitudinal/lateral configuration.

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